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OCEAN MIXED LAYER BIOLOGICAL RESPONSE TO TRANSIENT OCEAN EVENTS

by

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OCEAN MIXED LAYER BIOLOGICAL RESPONSE TO TRANSIENT OCEAN EVENTS

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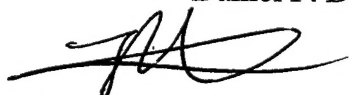
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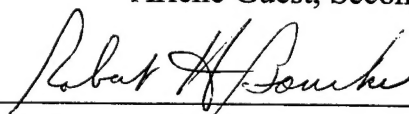
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ABSTRACT

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I. INTRODUCTION

In the past several years oceanographers have made significant advancements in understanding the physical processes that influence the organisms that reside in the upper ocean. This knowledge comes both from advances in modeling techniques and in improved sampling methods.

This study will continue from the work of Doney et al. (1996) and will focus on the advances in coupled physical/biological numerical modeling of the ocean mixed layer with an emphasis on the biological aspects. The biological effects following short duration transient events that result from dramatic changes in mixed layer forcing, such as strong winds will be examined. The results from two coupled physical/biological will be contrasted. The first model is a mixed layer model which represents the most basic biological interactions, with no component for detritus; the second model solves a more advanced set of equations with model components for both detritus and light.

A brief history and overview of biological modeling is given in Chapter II. In Chapter III the two models used here are described. Chapter IV discusses the results of these models, and Chapter V will summarize this work and make some recommendations for future work.

II. BACKGROUND

Our understanding of the physical, biological and chemical interactions that occur in the world's oceans has grown over the past several decades. This fact, coupled with an exponential growth in computer power, has enabled us to make great progress towards accurately modeling the physical and biochemical phenomena that are occurring in the ocean. This chapter will look at the development of biological modeling starting with Steel in1977 and progressing to current work by Doney (1996) and others.

Steel (1977) determined the most basic equations for biological interactions in the ocean. He pointed out many of the problems in biological modeling, the most obvious being the complex and, in some cases, poorly understood interactions among biological organisms. The interactions between physical and biological variables is still under investigation today and will continue well into the future. Steel's study provided the basis for more complex model development. The long term stability of populations of single cell plants and animals (phytoplankton and zooplankton) is primarily based on two classical challenges. The first is the cleverness of the animals whose feeding or reproductive behavior produces density dependent responses which induce stability. The second challenge is that the complexity of the physical environment may play a critical role in preventing instabilities from growing either through dispersion or mixing of populations over a range of habitats.

Steel (1977) derived the most basic equations for the concentrations of nutrients (N), phytoplankton (P) and herbivorous zooplankton (H). They are:

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$$\frac{dN}{dt} = -aNP + (b-c)PH + k(N_o - N)$$

$$\frac{dP}{dt} = aNP - bPH - kP;$$

$$\frac{dH}{dt} = cPH - dH;$$

where a is the phytoplankton growth rate and d is the zooplankton mortality rate. The grazing by H on P has the simple form of bPH, and the growth of H is some fraction of food intake ($c<b$). These equations are based on a simple two layered ocean (Figure 1) and the concentrations of N, P and H are normalized on standard or average values so that of N, P and H are dimensionless. The units of the model constants are in t^{-1}. It is also assumed that all production takes place in the upper mixed layer since the lower layer is assumed to have a light intensity too low for production to occur and diurnal migrations of zooplankton are disregarded in these equations. This set of equations is more thoroughly described in Chapter III and the model results are discussed in Chapter IV.

Dissolved nutrient (N)   Phytoplankton (P)   Zooplankton (Z) diurnal migration
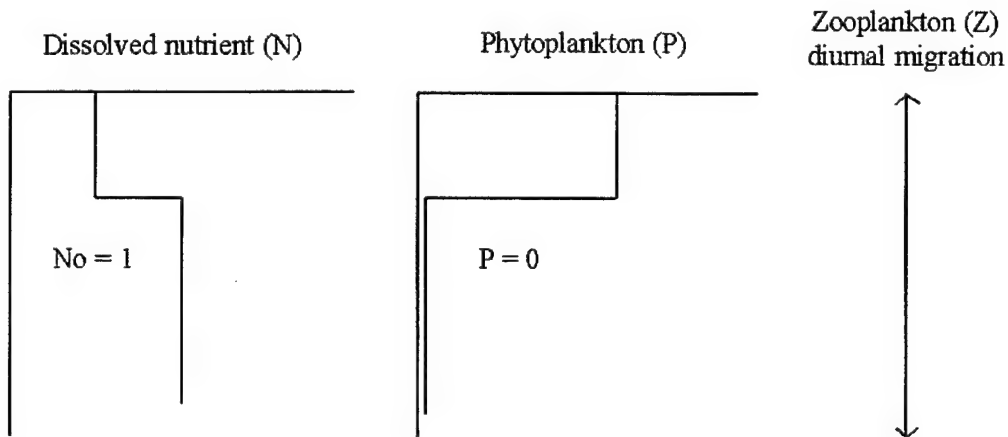
No = 1   P = 0

Figure. 1 - A simple representation of a two-layer ecosystem. Reproduced from Steel (1977)

Franks et. al (1986) developed a nutrient-phytoplankton-zooplankton (NPZ) model based on a modified version of the function experimentally determined by Mayzaud and Poulet in 1978. They compared their results to models based on the traditional Ivlev grazing expressions in which there is no asymptotic limit to the grazing rate. Their model showed highly damped oscillations in response to high grazing pressure as it approached steady state.

In their conclusions they noted that in other experimental ecosystems such as CEPEX, MERL and Loch Ewe bag experiments that the biomass as a whole tended toward some equilibrium value. Species' successions were seen in these experiments but the system did generally follow a non-oscillatory trend and approached some steady state. Franks believes that the Mayzaud and Poulet formulation allows a more predictable and robust model behavior and he suggested that it allows for a more realistic simulation of gross phytoplankton dynamics. Their results are displayed in Figure (2).
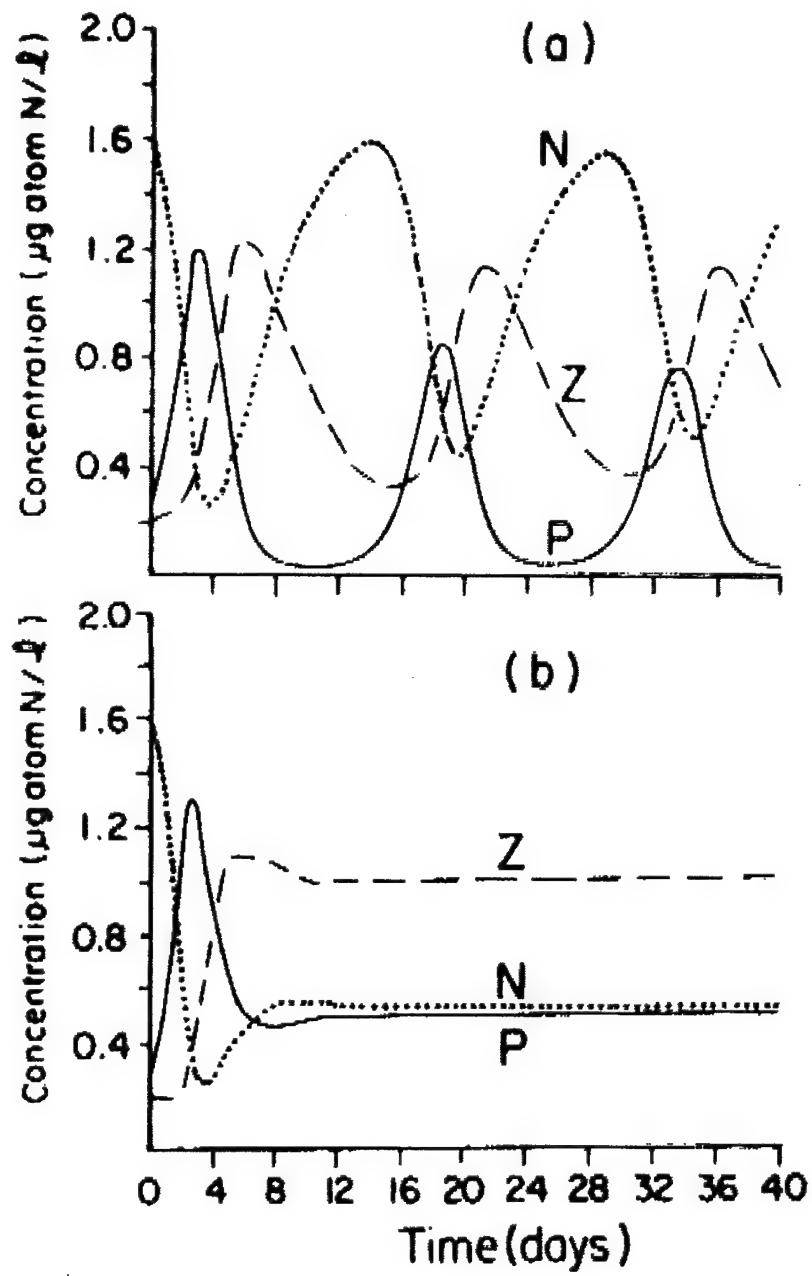
Figure 2. Time-dependent behavior of two types of herbivore grazing: (a) Ivlev and (b) Mayzaud and Poulet, from Franks et al. (1986).

Frost (1987) described seasonal variation of phytoplankton stock and production at ocean Station P (50° N 145° W). His model was designed to reproduce seasonal variations and integrated interactions of specific physical, chemical, and biological components of the subarctic pelagic ecosystem, and to simulate the observed level of phytoplankton production.

In his model horizontal advection and diffusion were ignored. In addition, the phytoplankton were restricted to the mixed layer which was an oversimplification, but eliminated the need for detailed parameterization of mixing and phytoplankton growth and grazing mortality within the pycnocline. He also assumed that, in general, phytoplankton are uniformly distributed in the mixed layer at Station "P" and there is no subsurface maximum; that is, the mixed layer is homogeneous with respect to phytoplankton.

Fasham et al. (1990) presented a model of the annual cycles of plankton dynamics and nitrogen cycling in the oceanic mixed layer. This model was customized for Station "S" near Bermuda and utilized seven compartments or modules (Phytoplankton, Zooplankton, Bacteria, Nitrate, Ammonium, Dissolved organic nitrogen and Detritus). They found that one of the controlling parameters was the detritus sinking rates, for which they used values of 1 and 10 m/day. Due to the comparatively slow transition of detritus material into nutrients, it was found that the detritus only had a significant influence when sinking rates were on the order of 1 m/day.

Fasham's overall objective was to model the seasonal cycles of plankton and nutrients in the global ocean, in order to learn more about he role of oceanic organisms in

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regulating the atmospheric CO_2 content. In his model, nitrogen is considered the limiting nutrient of primary production. The main physical forcing parameters in the model are the annual cycles of mixed layer depth and solar radiation.

Fasham's model is lacking in the physical aspects. His model does not include such processes as changes in turbulent mixing, effects of internal waves, seasonal changes in the diffusive mixing across the thermocline and within the mixed layer, and since it is only a 1-D model it does not include any horizontal advection.

Aksnes and Lie (1990) presented a vertically resolved model for the land-locked fjord Lindåspollen, in western Norway. They found that primary production above the pycnocline is nutrient limited, while below the pycnocline the production is both nutrient and light limited. Hence, the new production during summer is controlled mainly by three factors: (1) the light availability in the deep nutrient-rich water, which depends on the intensity of the solar radiation and the turbidity of the water, (2) the turbulent diffusion of nutrients within the watermasses above the pycnocline, and (3) the nutrients supplied by freshwater runoff to the layer above the pycnocline.

Aksnes and Egge (1991) discuss the difficulties in obtaining accurate nutrient uptake parameters and state that currently oceanographers are only trying to evaluate orders of magnitude vice actual rates. Nutrient uptake refers to processes necessary for moving a nutrient (denoted as an ion) from the outside to the inside of a cell (or perhaps to a site where further processing of the ion takes place.) The rate of nutrient uptake depends on the time period needed for transfer of nutrient ions from the outside to the inside of the cell, but also on the time elapsing between encounters of nutrient ions and

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uptake sites. Increased temperature generally means higher biochemical rates. Thus it is reasonable that increased temperature will lead to shorter handling times because handling involves biochemical processes. Handling time is defined as the time interval where uptake of an ion at an uptake site is prevented because of handling of another ion.

In a WHOI Technical Report, Davis and Steel (1994) reported on the findings of a five day workshop in June 1993 on the status of upper layer biological/physical modeling. A summary of critical issues was presented, and the following conclusions were drawn:

- Horizontal variability is not well known

- Lagrangian nature of flows is not well known

- Future acoustic observational techniques will help resolve turbulence fields.

During this workshop the members used three physical models, a simple conventional mixed layer model, PWP model Price et al. (1986) and the MY Mellor and Yamada (1982) level 2.5 model. These models were coupled with various versions of NPZ and NPZD biological models and some results of the various coupled models were presented. The report went on to discuss the effectiveness of the various mixed layer models.

Stramska and Dickey (1994) present a simple short time scale NPZ model. Like other models their model cannot simulate effects related to horizontal variability, processes such as photoadaptation and photoinhibition, or biological diversity of phytoplankton populations. They also noted that because of the numerous physical and biological factors controlling both growth and losses of phytoplankton, models describing annual phytoplankton cycles must be rather exhaustive and contain considerable numbers

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of equations and parameters. As a result, it is often difficult to evaluate to what degree

the modeling results are affected by a particular assumption. In the case of extremely

deep mixing events due to strong winds and surface heat loss, significant removal of

phytoplankton stock from the euphotic zone occurs.

Doney et al. (1996) designed a coupled 1-D biological/physical mixed layer model

utilizing detailed boundary layer physics and relatively simple biological interactions.

Doney noted that Fasham et al. (1990) used biological models that are too complex based

on our limited knowledge of the coupling between ocean planetary boundary layer (PBL)

physics and biological vertical structure and fluxes. Phytoplankton growth in Doney's

model is controlled by nutrient and light limitations, and phytoplankton losses occur via

natural mortality, zooplankton grazing and phytoplankton aggregation. The latter two

processes lead to the production of sinking detrital particles. Doney's model incorporates

four compartments for phytoplankton, zooplankton, nutrients and detritus. One

difference that Doney applied was the variations in phytoplankton chlorophyll to nitrogen

ratios (chl:N).

A one dimensional coupled biological and physical model for the Black Sea was

proposed and tested by Oguz et al. (1996). For the physical model they used the Mellor-

Yamada level 2.5 closure scheme. The biological part of the model involved interactions

between inorganic nitrogen (nitrates and ammonium), phytoplankton, herbivorous

zooplankton and detritus. In this model nitrogen is considered to be the limiting factor in

primary production. The phytoplankton production process is parameterized in terms of

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Liebig's law which assumes either lack of nutrients or light controls the biological productivity.

The biological model requires a choice of 16 externally imposed parameters. Most of these parameters are poorly known from the observations. Determination of the values of the rate constants is one of the most difficult problems which ongoing research and observations will continue to verify and improve in the future.

Oguz found that the initiation of the spring bloom depends strongly on the local mixing conditions and follows the weakening of the convective overturning mechanism. As soon as the surface layer of the water column gains a slight stability, the bloom commences before the formation of the seasonal thermocline. This model is capable of reproducing basic features of the plankton-nutrient fields in the Black Sea and helps us understand and interpret the available observations. To make this model more realistic it would need the introduction of the high-frequency variability and thus incorporation of strong wind-induced mixing, and parameterization of intermittent lateral nutrient input into the surface layer.

Smythe et al. (1997) quantified the decay rate of subsurface turbulence using data obtained during several squalls that occurred in the western equatorial Pacific during the westerly windburst of December 1992. The ocean was generally well-mixed down to about 70 m (the top of the main thermocline) due to persistent strong winds associated with the windburst. They found that a typical squall event coincided with the appearance of a layer of relatively cool, fresh, highly turbulent water in the upper few meters. The

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layer remained distinct from the underlying water for several hours after the squall had passed, during which time it spread to a depth of 10-30 m.

They took successive profiles of viscous dissipation rates (ϵ) following each of the squalls and found that within the squall layer, dissipation rates increased by an order of magnitude coincident with the increase in surface forcing. Below the squall layer, an equally dramatic decrease in ϵ is evident.

The observed suppression of subsurface turbulence provided some clues about the manner by which the turbulence was originally generated. They hypothesized that the mechanism for local TKE maintenance was a downward flux of surface-generated turbulence. Prior to squall passage, weak stratification allowed surface-generated turbulence to be readily distributed over the upper few tens of meters. This suggests that at least a significant fraction of ambient turbulence was driven by wind and buoyancy forcing. However, with the onset of heavy precipitation, near-surface stability characteristics change dramatically. The base of the squall layer is characterized by intense static stability due to salinity stratification. This stable stratification acted to inhibit downward transport of turbulence, thereby concentrating surface-generated turbulence within the squall layer. With the flux of turbulence from the surface thus suppressed, turbulence levels in the region below the squall layer decayed.

III. MODEL DESCRIPTIONS

The two coupled physical/biological models will be described in this section.

Both of the models were written in MATLAB code. The physical half of the model

remained the same while varying the complexity of the biological component.

A.   THE PHYSICAL MODEL

The physical half of the model is solved using the Runge-Kutta method with a

variable time step to solve the mixed layer equations. The numerical scheme maximizes

the time step to solve the set of equations without exceeding specified error tolerances. In

mixed layer physics when mixed layer shallowing occurs, $\partial h/dt$ is not a continuous

function. Therefore, the Runge-Kutta solution can only be used during periods of mixed

layer deepening. Due to the short time steps and the inclusion of TKE unsteadiness, this

model is ideally suited for predicting transient events and spin-up and spin-down of

turbulence. The basic physical differential equations used are:

Mixed Layer Depth

$$\frac{\partial(h)}{\partial t} = w_e - \overline{W}_{z=-h} \tag{1}$$

Total TKE

$$\frac{\partial(h\overline{E})}{\partial t} = 2m_3 u_*^3 + (\overline{u}^2 + \overline{v}^2)w_e - (\alpha gh\Delta\overline{T})w_e - \alpha gh\frac{Q_o}{\rho c_p} - D \tag{2}$$

Vertical TKE

$$\frac{\partial(h\overline{w'}^2)}{\partial t} = -(\alpha gh\Delta\overline{T})w_e - \alpha gh\frac{Q_o}{\rho c_p} + R - \frac{D}{3} \tag{3}$$

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Mixed Layer Temperature

$$\frac{\partial(\bar{T})}{\partial t} = \frac{Q_o}{\rho c_p h} - \Delta \bar{T} \frac{w_e}{h} \tag{4}$$

Easterly Velocity

$$\frac{\partial(h\bar{u})}{\partial t} = fh\bar{v} + \frac{\tau_x}{\rho} \tag{5}$$

Northerly Velocity

$$\frac{\partial(h\bar{v})}{\partial t} = -fh\bar{u} + \frac{\tau_y}{\rho} \tag{6}$$

Equation (1) defines the mixed layer depth, which can change due to the entrainment velocity, w_e, and any upwelling or downwelling ($\overline{W}_{z=-h}$). Equations (2) and (3) calculate total turbulent kinetic energy (TKE) times h and vertical TKE times **h** respectively. Equation (4) calculates mixed layer temperature, which is governed by the surface heat flux and entrainment heat flux. Equations (5) and (6) are used to find the easterly velocity (**u**) times **h** and the northerly velocity (**v**) times h.

For a more complete description of the physical processes refer to Stone (1997) and Garwood (1977).

B.   THE BIOLOGICAL MODEL

The first version of the biological model is based on the equations developed by Steel (1977) based on the well-known Lotka-Volterra predator-prey relations. The equations have been modified to include terms for nutrient and phytoplankton entrainment. In this model, terms for Detritus (waste matter and decaying organisms which in turn produce nutrients) have been neglected. The equations are:

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$$\frac{\partial}{\partial t} <N> = -a <P><N> +(b-c)<P><H> - \frac{\Delta N w_e}{h} \qquad (7)$$

$$\frac{\partial}{\partial t} <P> = a <P><N> -b <P><H> - \frac{\Delta P w_e}{h} \qquad (8)$$

$$\frac{\partial}{\partial t} <H> = c <P><H> -d <H> \qquad (9)$$

where **N** is nutrients, **P** is phytoplankton, **H** is single-cell herbivores (or zooplankton), w_e is entrainment and h is the mixed layer depth. The $<>$ denotes the time average mean value. A conceptual view of this three component biological model is shown in Figure 3. In this simple model the phytoplankton consume the nutrients. Some of the phytoplankton are consumed by the zooplankton and others die and are returned to the system as nutrients. The zooplankton produce waste matter and eventually die, both by products are then returned to the system as nutrients.
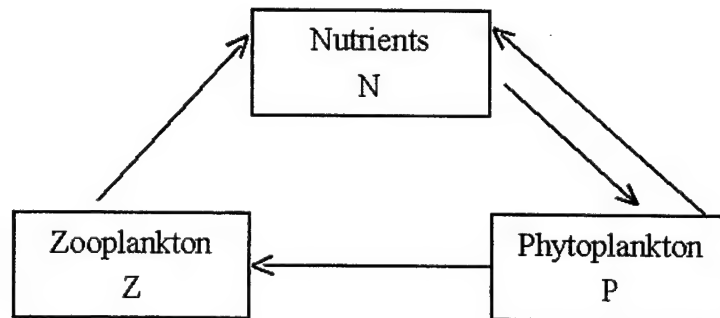
Figure 3. Schematic diagram of the three component biological model showing the flow pathways.

Four constants are needed; the phytoplankton growth rate, (**a**), the growth by grazing term, (**b**), the recycled waste from grazing term, (**c**), and the zooplankton death

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term (**d**). The values chosen for these were a = 2.0/day, b = 1.5/day, c = 1.2/day, and d = 0.2/day.

When determining how to use the nutrients, all of the elements that make up nutrients, such as nitrates, nitrites and phosphates, are grouped together in a general term as nutrients. This is an area where large generalizations are made for the biological model. I assumed a normalized value of 1 for concentration of nutrients below the mixed layer and a value less than 1 for concentration of nutrients within the mixed layer. To initialize the model, a value of 0.1 was chosen for the concentration of nutrients in the mixed layer.

For the phytoplankton, the different species are combined into a single term. Since phytoplankton are very dependent on light they typically only reside in the euphotic zone (the area of greater than 1% light intensity of the surface light level). The mixed layer depth (MLD) and the euphotic zone are assumed to be the same. Therefore, the phytoplankton can only reside in the mixed layer (normalized concentration of 1) and are zero below the mixed layer. A value of 0.01 was chosen to initialize the model.

Similar simplifications are made for modeling the zooplankton. Herbivorous zooplankton have the ability to propel themselves through the water and often have a diurnal cycle depending upon the species. Zooplankton are not dependent upon light and are not confined to the mixed layer. However, for the model, it is assumed that the zooplankton are not species specific and are going to remain in the vicinity of their food source (the phytoplankton) and are not going to have diurnal migrations. The concentration for zooplankton used to initialize the model is 0.01.

The second, more advanced biological model is based on the Davis, Olson and Flierl NPZD model outlined in Davis and Steel (1994) which is derived from the Flierl and Davis (1993) NPZ model. The set of coefficients was also taken from Davis and Steel (1994) and is outlined in Table 1. Most of the values are accepted for diatom/copepod dominated food webs, based on historical observations and experimental data. The coefficients with the lowest degree of accuracy are the zooplankton death rate (zd), the detritus remineralization rate (rd), and the phytoplankton death rate (pd). All other assumptions made for the previous biological model remained the same for this model. The schematic diagram of the model showing the pathways and directions of flows between the four compartments is displayed in Figure 2.

In the second version of the model a solar radiation component was added and was modeled based on Frost (1987) and Oguz et al. (1996). This exponential relationship is:

$$I(z) = I_0 \exp(-(kw * (P * kc))z \tag{10}$$

where I(z) is the solar radiation at depth z. The model has the capacity to toggle I(z) on and off to simulate a diurnal variation. I_0 is the incident solar radiation at the surface corrected to only account for photosynthetically active radiation (PAR). There is some debate over the actual PAR value. Frost (1987) and Oguz et al. (1996) concluded the value to be 50%. Later Frost (1993) used a value of 70%, Asknes & Lie (1990) determined the value to be 25% while Skogen et al. (1995) used a PAR value of 40%. A

PAR of 50% was chosen for this study. The extinction coefficient for attenuation due to sea water is kw and kc*P represents the attenuation due to phytoplankton in the water column. Again there has been some debate over these coefficients. For this research, values of kw and kc were taken from Oguz et al. (1996) and are kw = 0.08 and kc = 0.07. A more thorough explanation of light attenuation characteristics in sea water may be found in White (1991) and Cullen (1990).
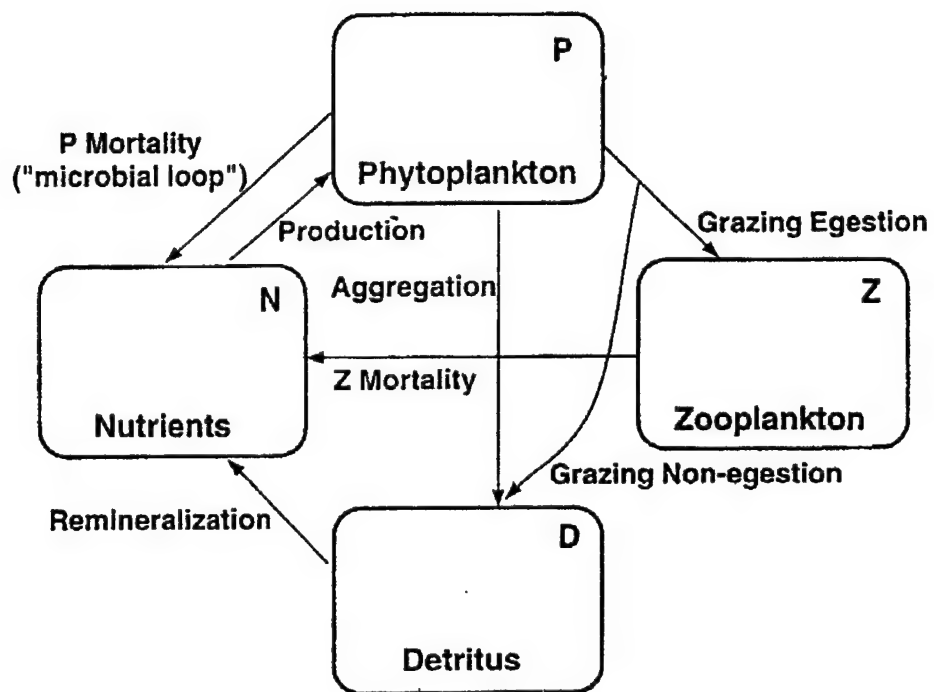
Figure 4. Schematic diagram of the four component biological model showing the flow pathways. Reprinted from Doney et al. (1996).

The advanced set of equations are as follows:

Nutrients:

$$\frac{dN}{dt} = -pg * P * N * PAR + (ae - ge) * gr * P * Z + ae * zd * Z + rd * D - nent \qquad (11)$$

Phytoplankton:

$$\frac{dP}{dt} = pg * P * N * I - gr * P * Z - pd * P - pent \qquad (12)$$

Zooplankton:

$$\frac{dZ}{dt} = ge * gr * P * Z - zd * Z \qquad (13)$$

Detritus:

$$\frac{dD}{dt} = (1 - ae) * gr * P * Z + (1 - ae) * zd * Z + pd * P - rd * D \qquad (14)$$

where:

nutrient uptake	$= pg * P * N * PAR$
grazing	$= gr * P * Z$
phytoplankton death	$= pd * P$
zooplankton death	$= zd * Z$
detritus remineralization	$= rd * D$

Table 1 defines the above terms, including units and initial conditions where applicable.

Biological Model Components and units

DESCRIPTION	SYMBOL	INITIAL VALUE	UNITS
Nutrient Concentration (Summer)	N	0.1	dimensionless
Nutrient Concentration (Winter)	N	1.0	dimensionless
Phytoplankton Concentration	P	0.01	dimensionless
Zooplankton Concentration	Z	0.01	dimensionless
Detritus Concentration	D	0.01	dimensionless
Solar Radiation (Summer)	PAR	100	w/m^2
Solar Radiation (Winter)	PAR	75	w/m^2
Phytoplankton Growth Rate	pg	0.3	/day
Zooplankton Grazing Rate	gr	0.70	/day
Zooplankton Death Rate	zd	0.05	/day
Detritus Remineralization Rate	rd	0.2	/day
Phytoplankton Death Rate	pd	0.05	/day
Growth Efficiency for Z	ge	0.35	dimensionless
Assimilation efficiency for Z	ae	0.70	dimensionless

Table 1: Initial conditions for advanced biological model.

In this model the phytoplankton growth rate is linearly dependent upon both light and nutrients. The zooplankton grazing rate is linearly dependent on the phytoplankton biomass. The detritus module is a simple "microbial loop" where the detritus remineralization rate (*rd*) is the rate at which bacteria convert detritus-nitrogen to dissolved nitrogen.

IV. RESULTS

This study begins by using a simple NPZ model based on Steel (1977). The purpose of the first run was to compare to Franks et al. (1986) to the NPZ model used in this study. In this run an average mixed layer temperature was used vice a temperature "jump" at the bottom of the mixed layer. The zooplankton death rate (0.2/day) and the growth by grazing term (1.5/day) were taken from Franks et al. (1986). The other two initial condition variables were taken from an average of values given in several references. Figure 2 displays the results from the Franks model and Figure 5 displays the results from the NPZ model used here.

The results of the two models are similar in that they both start with an initial oscillation of N, P and Z and then both approach a steady state. The Franks model attains a steady state in approximately 12 days as compared to approximately 20 days to attain a nearly steady state condition for the NPZ model used here. The differences in time are a result of the more complex biological interactions included in the Franks model. The key result here is the fact that both models do attain a quasi-steady state.
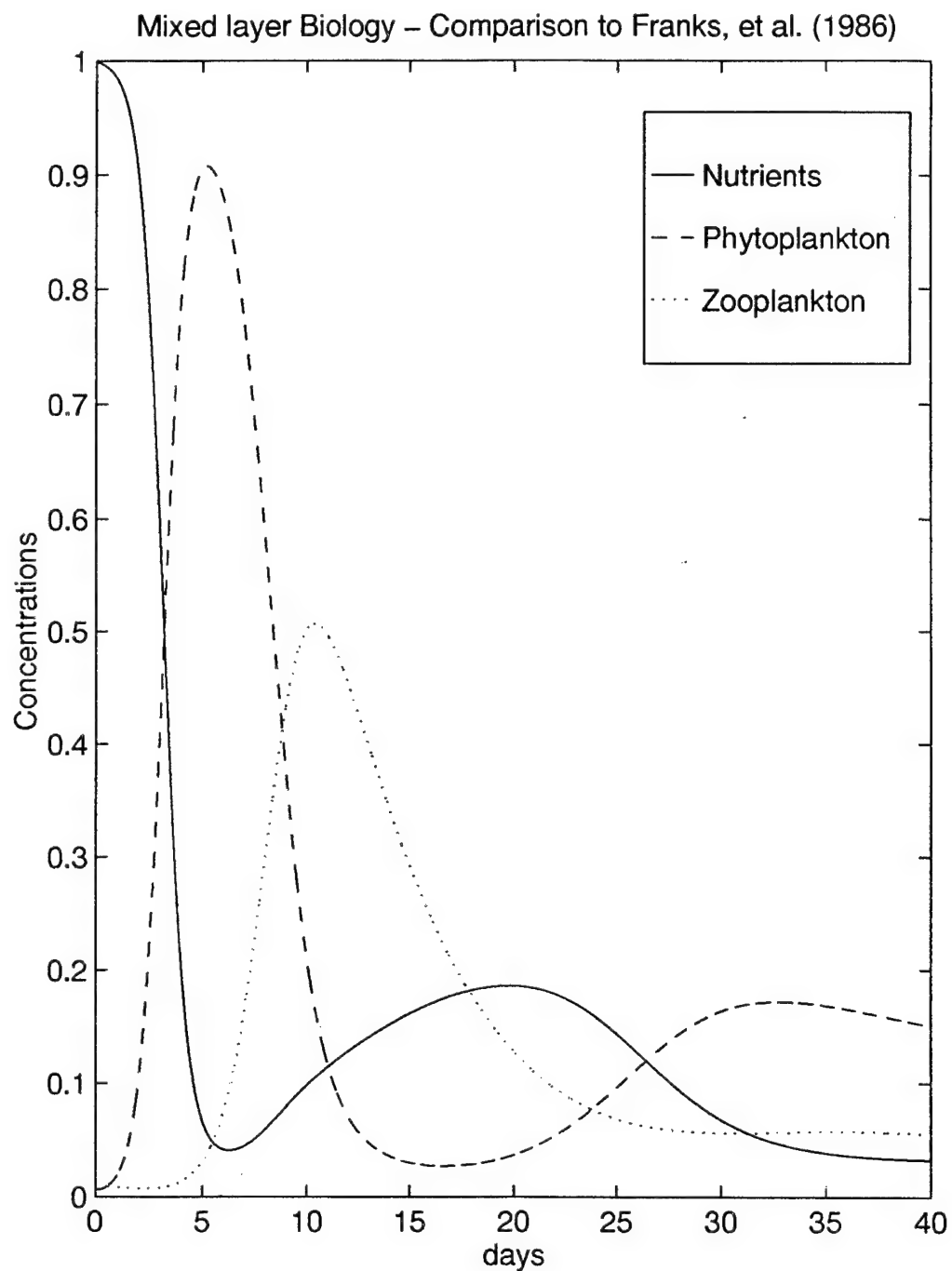
Figure 5. Mixed layer biology initialized in calm to moderate wind conditions. Q =
0.001 cal/cm^2/s and τ = 1.0 dynes/cm^2 utilizing an average mixed layer temperature. For
comparison to Franks et al. (1986).

In the next case the NPZ model was initialized in calmer conditions (wind stress (τ) = 0.5 dynes/cm^2 and net heat flux (Q) = 0.001 cal/cm^2/s). A highly stratified mixed layer was assumed with sea surface temperature of 20.0 $^\circ$C and a -5.0 $^\circ$C jump at the bottom of the mixed layer. The initial mixed layer depth was 10m.

Figure 6a displays the evolution of the mixed layer biology from this run. Of interest is the fact that the system takes approximately 40 days to reach a nearly steady state condition. In addition, the concentration values are much lower than with a stronger wind stress. Figure 6b displays the TKE, mixed layer depth and horizontal currents for this case. In this case the mixed layer only reached a depth of 17 m in this 40 day run.

The long time to attain a steady state, the low biological concentrations and the shallow mixed layer are a result of the low surface wind stress value. With a low wind stress the turbulent mixing is low and the entrainment of nutrients into the mixed layer is slow. As will be shown in the following figures, with increasing wind stress, the entrainment rapidly increases and the system will tend towards some steady state much more quickly.
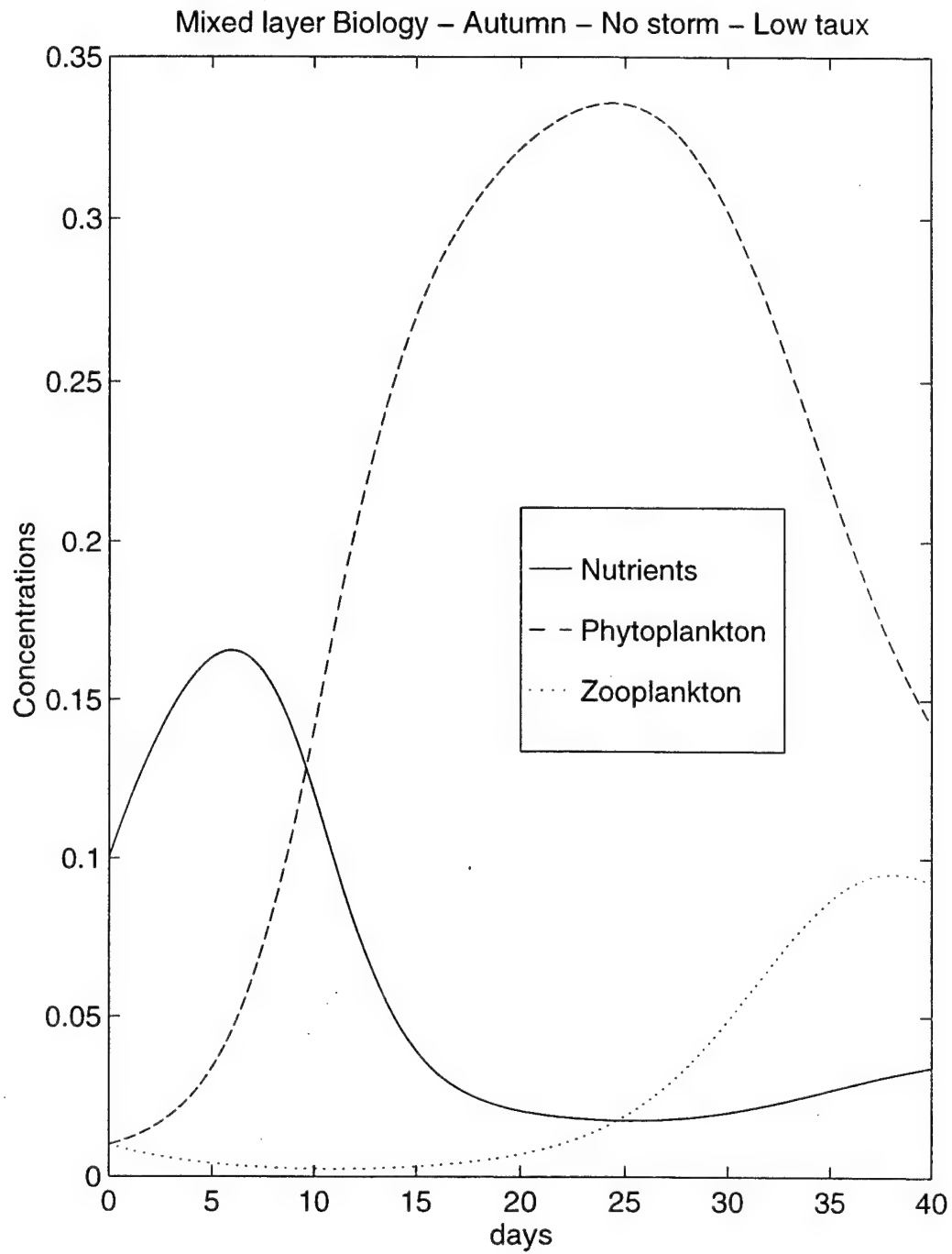
Figure 6a. Mixed layer biology initialized in calm conditions. $Q = 0.001$ cal/cm^2/s and $\tau = 0.5$ dynes/cm^2.
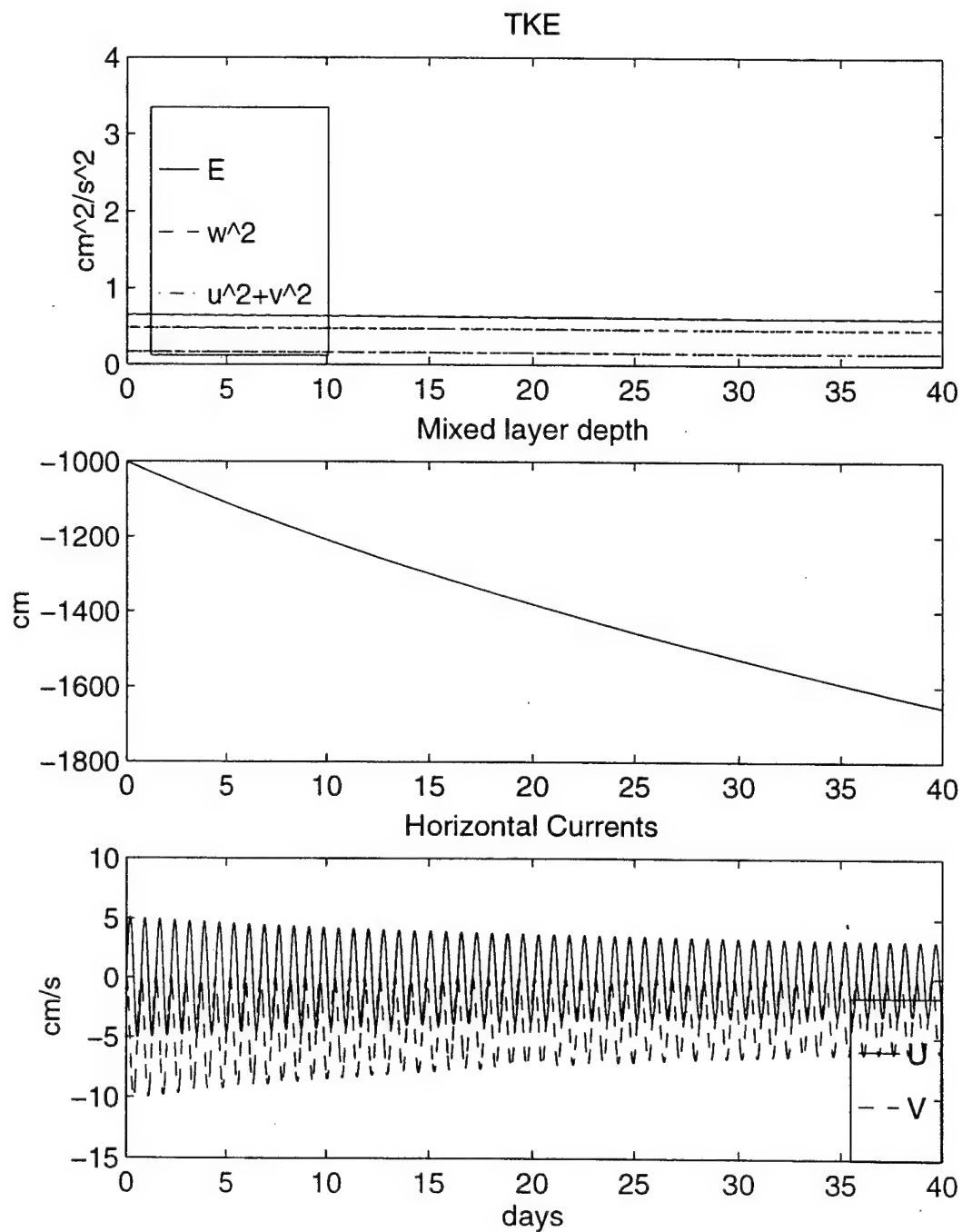
Figure 6b. TKE, mixed layer depth and horizontal currents initialized in calm conditions. $Q = 0.001$ cal/cm^2/s and $\tau = 0.5$ dynes/cm^2.

The remaining results are all based on a series of four sets of conditions imposed on each of the three model versions. The first being the same NPZ model without terms for light or detritus. The second version utilizes the NPZ equations with terms for light included and the final version utilizes a set of more advanced NPZD equations with a light budget and terms for detritus. This provides for a progression of complexity in the models studied here in order to draw some conclusion about the effects of light and detritus in the short term.

The four sets of conditions are autumn with no storm induced during the run, autumn with a storm induce half way through the run, winter with no storm induced and winter with a storm induced. In each of the winter-time storm cases the mixed layer was found to deepen to very rapidly and to non-realistic depths. For that reason the winter storm cases are not presented here. Figure 7 graphically represents these four sets of conditions.

In all cases the initial mixed layer depth is 10m and the system has a net downward heat flux of $(Q) = 0.001$ cal/cm^2/s. For the autumn conditions an initial sea surface temperature of 20 $^{\circ}$C with a -5.0 $^{\circ}$C temperature jump at the bottom of the mixed layer is utilized. The nutrient concentration within the mixed layer is initially 0.1 and maximum of 1.0 below the mixed layer.

In the winter cases a much weaker stratification exists with the sea surface temperature of 15.1 $^{\circ}$C and a temperature jump of 0.1 $^{\circ}$C at the bottom of the mixed layer. In this winter case the initial nutrient level is 1.0 within the mixed layer.

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In the cases where a storm is induced, the storm forcing is immediately at a maximum value of wind stress (τ) = 2.0 dynes/cm^2 and net upward heat flux (Q) = -0.006 cal/cm^2/s. The storm condition is utilized for two days and then the wind stress value returns to (τ) = 1.0 dynes/cm^2; however the net heat flux is kept in the upward direction to prevent the model from trying to shallow the mixed layer depth, which would cause inaccurate results.
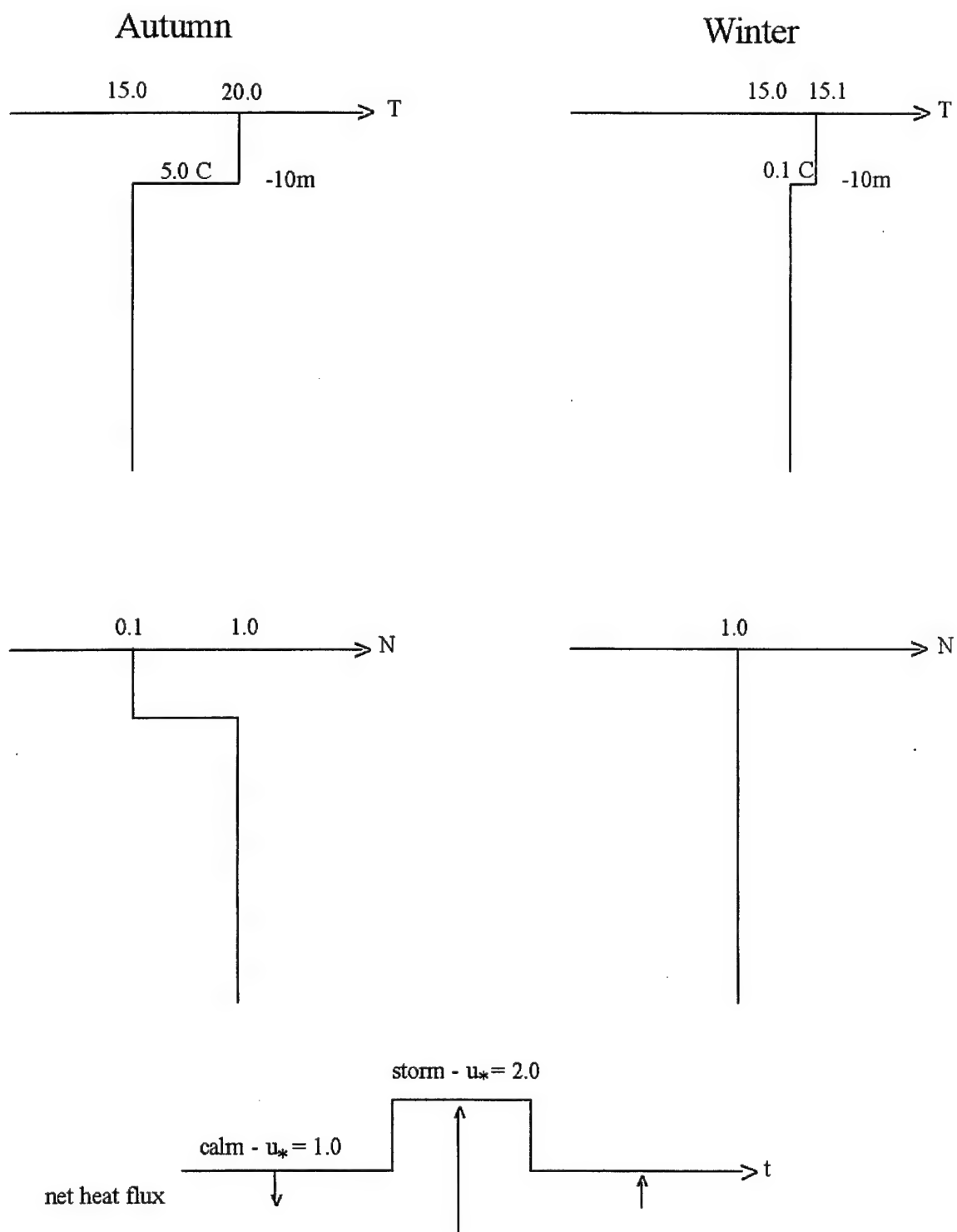
Autumn

15.0   20.0
⟶ T

5.0 C   -10m

Winter

15.0   15.1
⟶ T

0.1 C   -10m

0.1   1.0
⟶ N

1.0
⟶ N

storm - $u_* = 2.0$

calm - $u_* = 1.0$

⟶ t

net heat flux

Figure 7. Schematic diagram of the autumn and winter initial conditions and the storm conditions induced for these experiments.

The next four cases utilize the NPZ model with no terms for light or detritus. The initial mixed layer depth is 10m in all cases. Figure 8a shows the biological response with simulated autumn conditions of wind stress (τ) = 1.0 dynes/cm^2 and net downward heat flux (Q) = 0.001 cal/cm^2/s. No storm was induced in this run.

This case represents a standard baseline case for the next seven runs which all are some variation of this run. Note that the nutrient peak occurs at approximately day 4 and the phytoplankton peak at day 10, followed by the zooplankton peak at day 17. Maximum concentrations are approximately 0.43, 0.62 and 0.33 respectively. The system approaches a steady state at day 25.

Figure 8b displays the TKE, mixed layer depth and horizontal currents. Note that the mixed layer deepened to 70 m in this case.
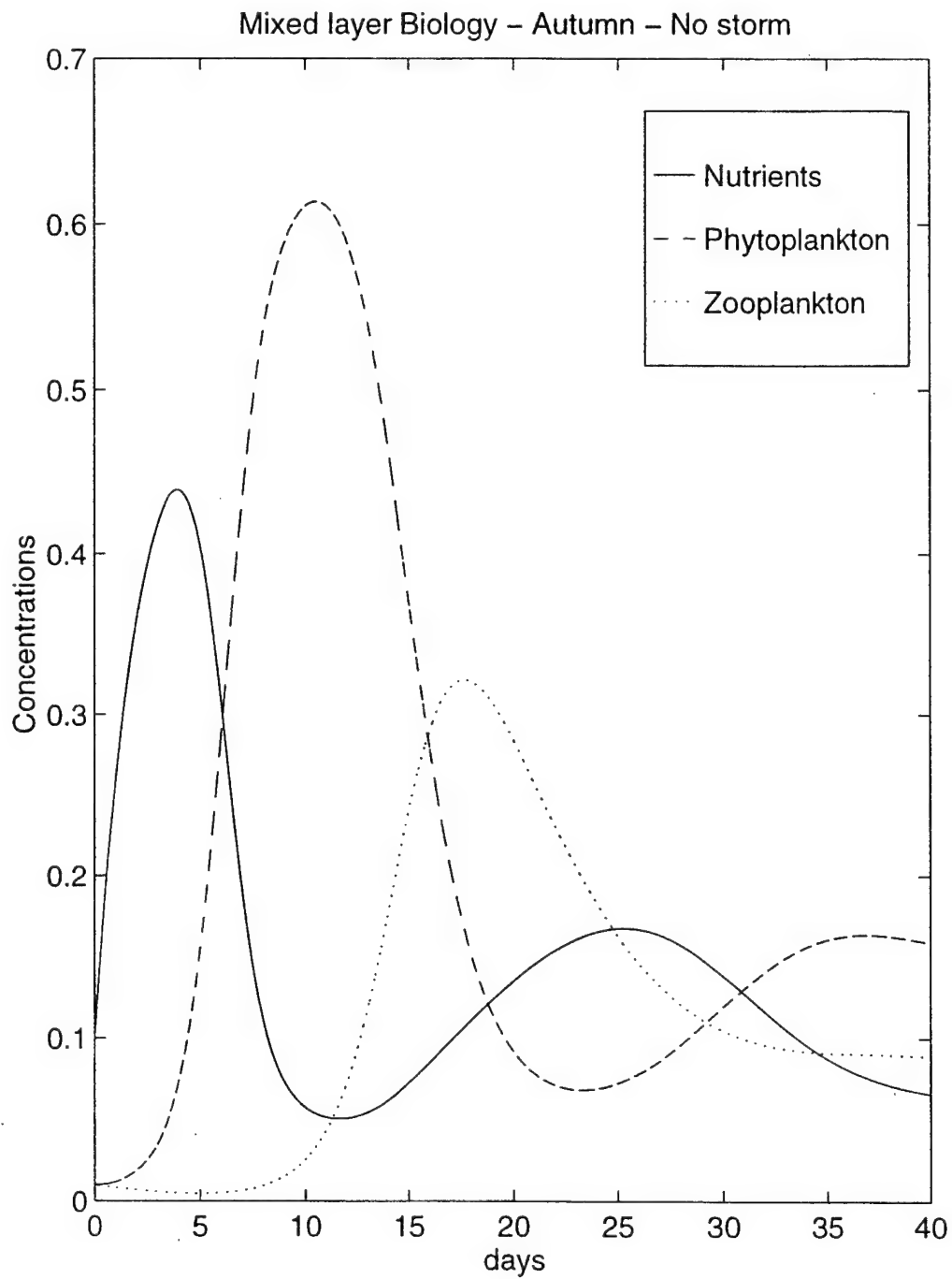
Figure 8a. Mixed layer biology initialized in autumn calm conditions (Q = 0.001 cal/cm²/s and τ = 1.0 dynes/cm²) and a strongly stratified water column.
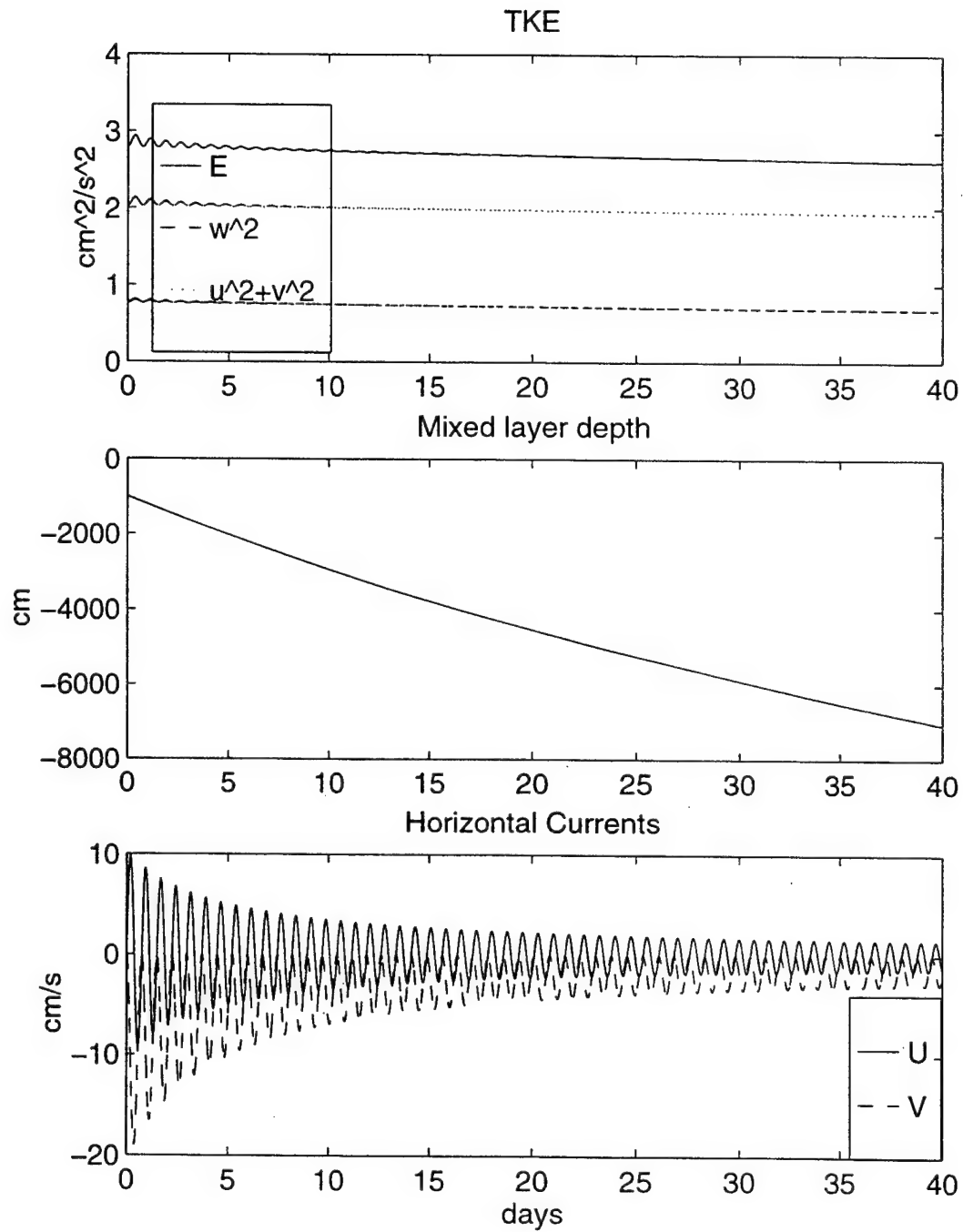
Figure 8b. TKE, mixed layer depth and horizontal currents initialized in autumn calm conditions (Q = 0.001 cal/cm^2/s and τ = 1.0 dynes/cm^2) and a strongly stratified water column.

The next run was initialized using the same conditions. In this run, however, a storm was induced on day 20 and stopped on day 22. The storm consisted on an increased wind stress (τ) = 2.0 dynes/cm^2 and a strong upward heat flux of (Q) = -0.006 cal/cm^2/s. After the storm was stopped on day 22 the wind stress was returned to pre-storm conditions and the heat flux was kept in the upward direction but with a magnitude of (Q) = -0.001 cal/cm^2/s.

Figure 9a displays the biological conditions through this 40 day run. When the storm is induced on day 20 there is sharp increase in the nutrient level as a result of the extra nutrients being entrained from below the mixed layer. Likewise, the phytoplankton and zooplankton peak four and nine days later respectively. Of interest in this Figure is the fact that the phytoplankton peak is lower than the zooplankton peak in the post storm conditions. This is due to increased level of zooplankton when the storm is initialized which consume the phytoplankton more rapidly than prior to the storm.

Figure 9b displays a dramatic increase in TKE when the storm is initiated at day 20. The mixed layer deepens slowly prior to the storm and then deepens rapidly after the storm starts. Since there is no resistance to the deepening once it has started, the mixed layer continues to deepen rapidly to a depth of 400 m. There is also a perturbation in the horizontal currents once the storm is initiated.
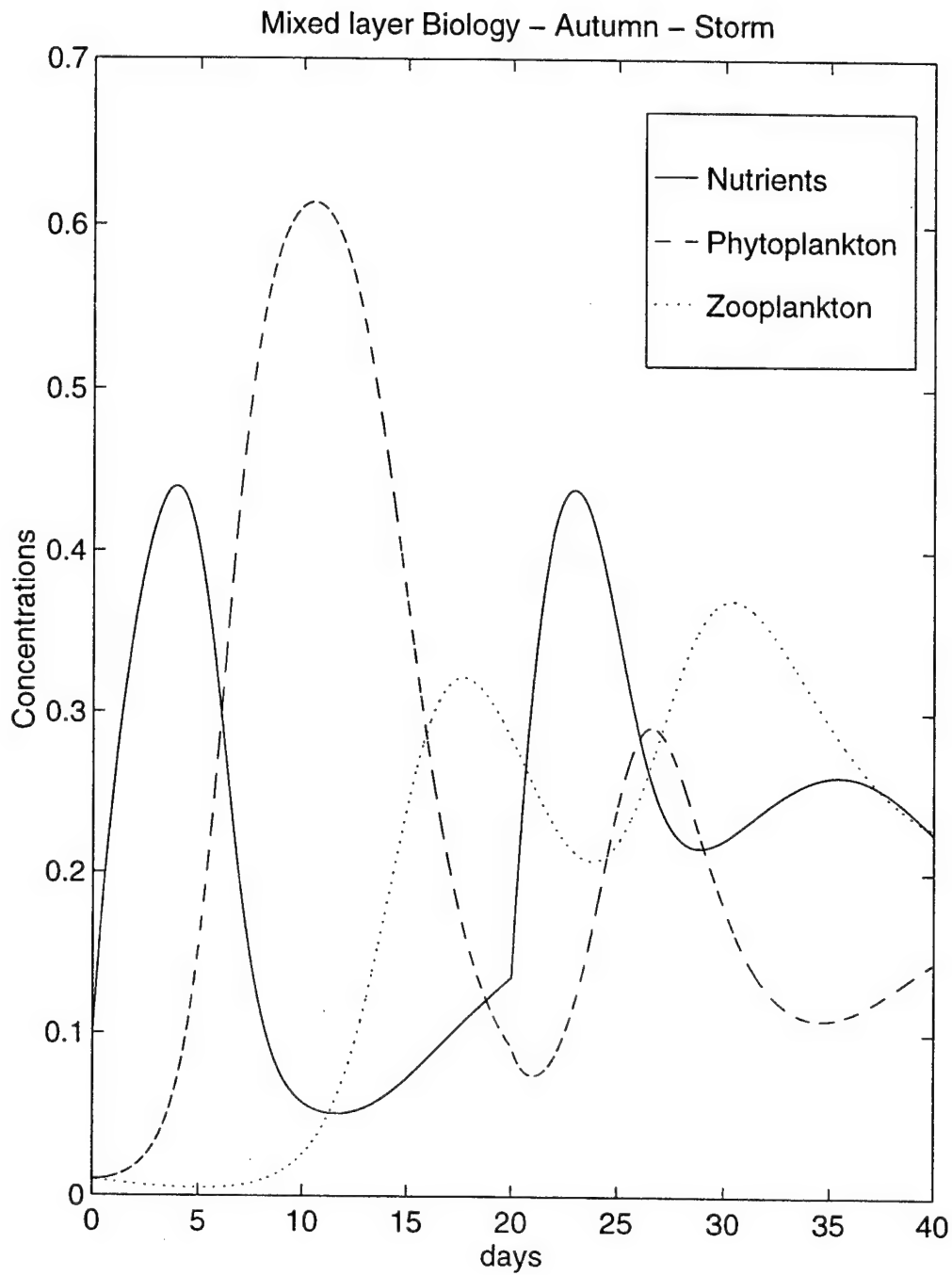
Figure 9a. Mixed layer biology initialized in calm autumn conditions($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) with storm induced on day 20 ($Q = -0.006$ cal/cm^2/s and $\tau = 2.0$ dynes/cm^2) and a strongly stratified water column.
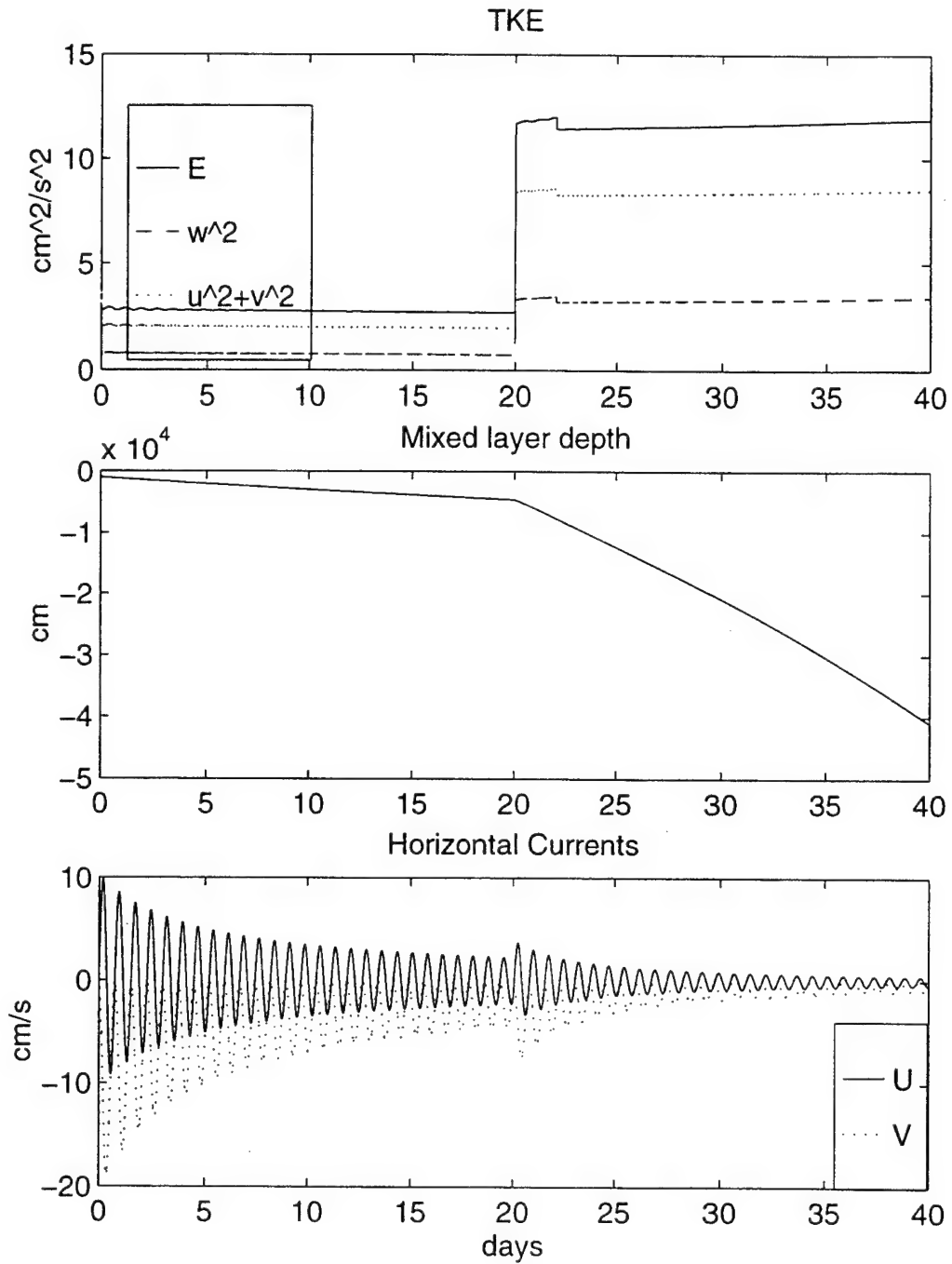
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Figure 9b. TKE, mixed layer depth and horizontal currents initialized in calm autumn conditions($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) with storm induced on day 20 ($Q = -0.006$ cal/cm^2/s and $\tau = 2.0$ dynes/cm^2) and a strongly stratified water column.

The next case is identical to the initial conditions that produced the results in Figures 8a and 8b except that these cases are initialized using a weakly stratified water column to represent winter-time conditions. This was done in the model by using a temperature jump of $-0.1\ ^{\circ}C$ at the bottom of the mixed layer. The level of nutrients was initialized with a maximum value of 1.0. All other initial conditions were the same.

Comparing Figures 8a and 10a one can easily see that the system approaches a steady state much more quickly. The phytoplankton peak in Figure 8a is at day 10 where as in Figure 10a the phytoplankton peak occurs at day six. Likewise the zooplankton peak occurs at day 17 in Figure 8a vice day 11 in Figure 10a.

Figure 10b shows the mixed layer deepening from the initial 10 m to 300 m in 40 days. Obviously, with this deep of a mixed layer light limiting the phytoplankton growth plays a very important role in attempting to accurately predict the biological reaction to these conditions. The attenuation of light would prohibit the growth of phytoplankton at only a few tens of meters below the surface. For this reason this case it believed to be grossly inaccurate and is only shown here to justify the necessity of including a light budget into the model. A winter time case with a storm induced will not be discussed here for the reason mentioned above.
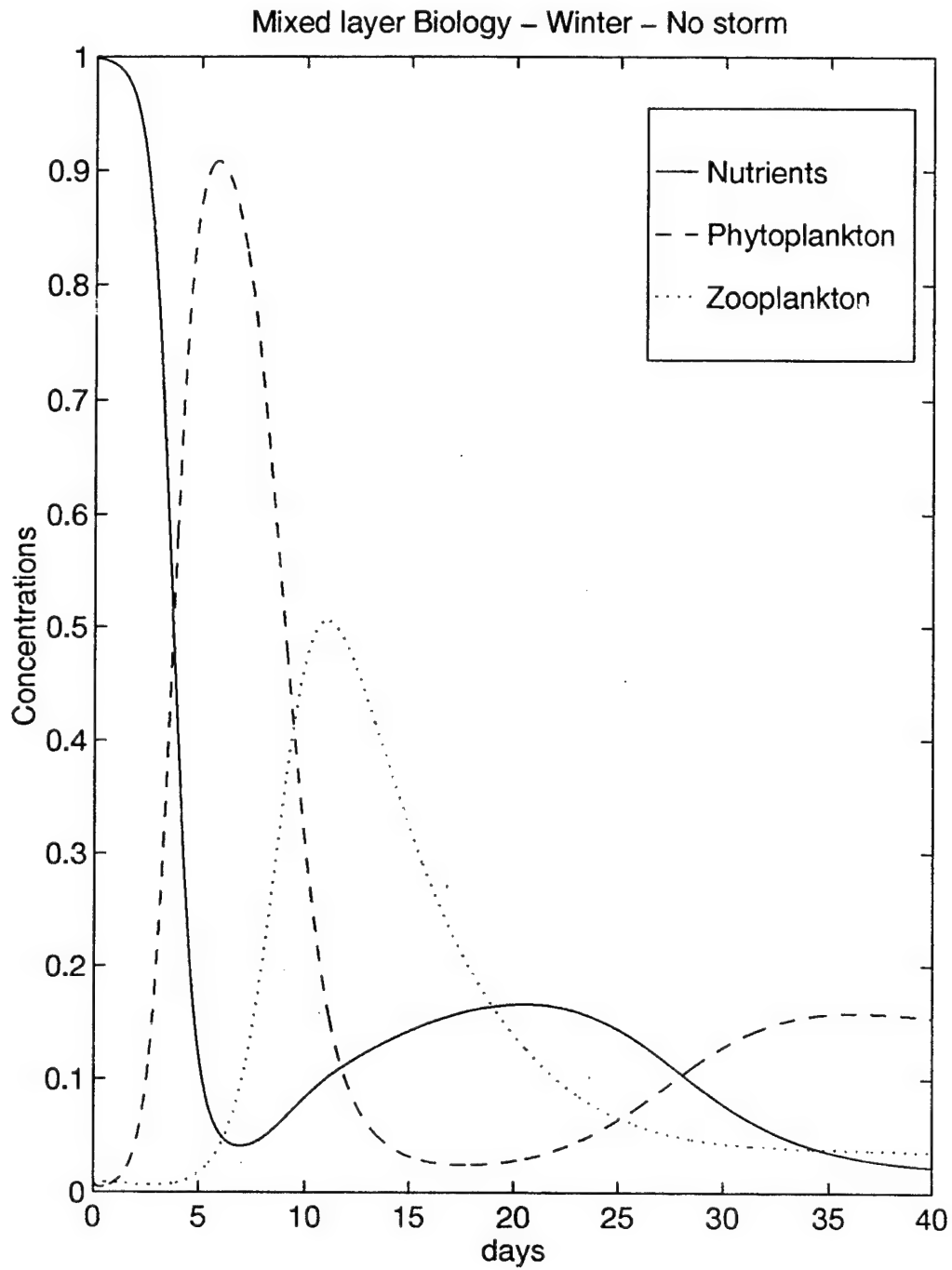
Figure 10a. Mixed layer biology initialized in autumn calm conditions (Q = 0.001 cal/cm2/s and τ = 1.0 dynes/cm^2) and a weakly stratified water column.
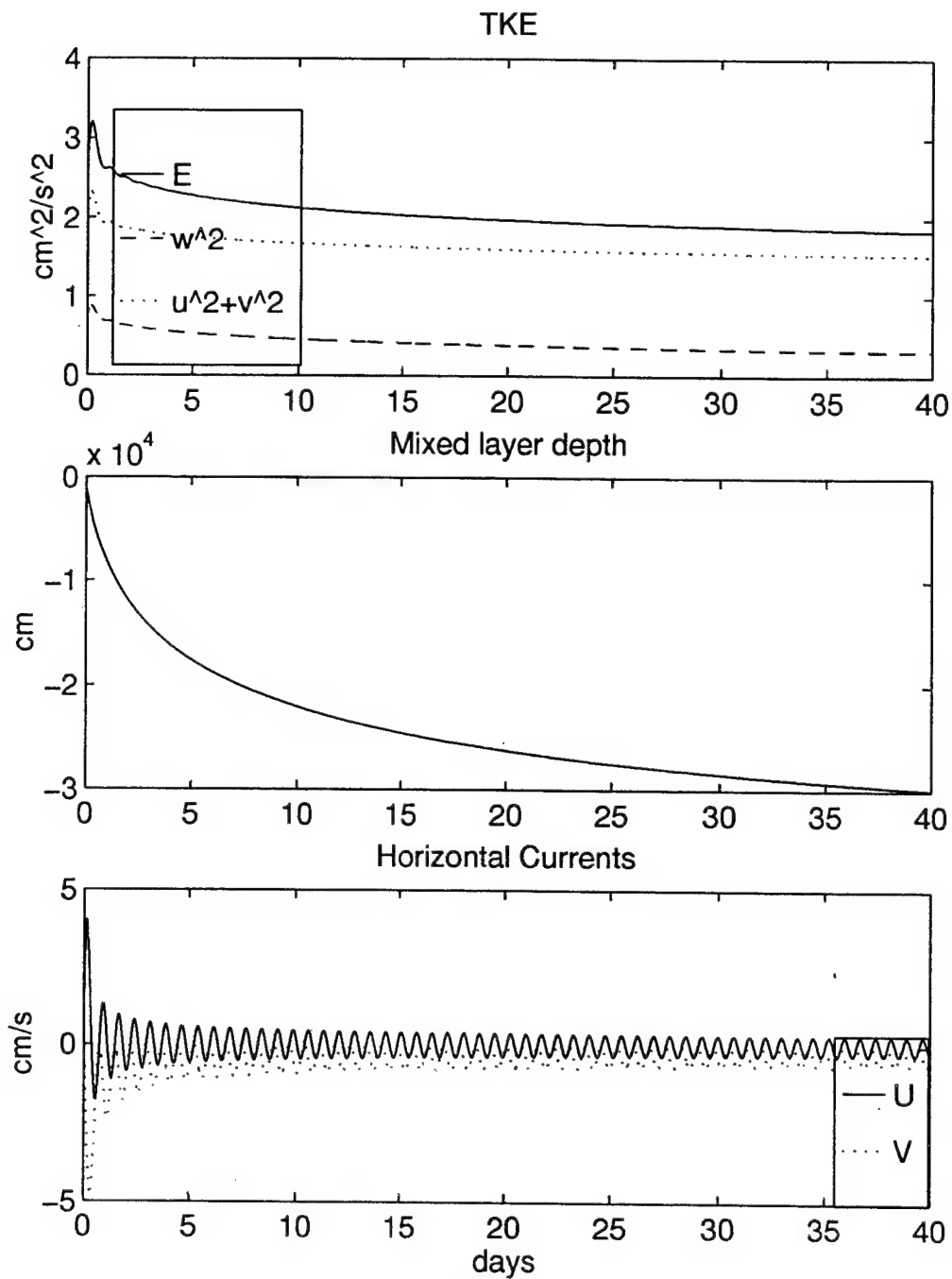
Figure 10b. TKE, mixed layer depth and horizontal currents initialized in calm autumn conditions($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) and a weakly stratified water column.

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In the next cases a light budget is added to the previously described NPZ model. The initial conditions are wind stress $\tau = 1.0$ dynes/cm^2, a net downward heat flux of Q = 0.001 cal/cm^2/s, a temperature jump of 5 ^{o}C at the bottom of the mixed layer and initial nutrient concentration of 0.1. Figure 11a displays the evolution of the mixed layer biology. The phytoplankton peak occurs at day 5 with a concentration of approximately 0.53. Compared to Figure 8a, the phytoplankton peak occurs 5 days earlier at a 20% higher concentration.

The nutrient level in this case drops to nearly zero very rapidly after the start of the run as a result of rapidly increasing phytoplankton which consume the nutrients. The zooplankton peak occurs with the same time interval from the phytoplankton peak as in the case with no light budget. This is because the zooplankton have no response to light conditions in this model.

As would be expected the TKE, mixed layer depth, and horizontal currents in Figure 11b are the same as in the model without the light budget (Figure 8b).
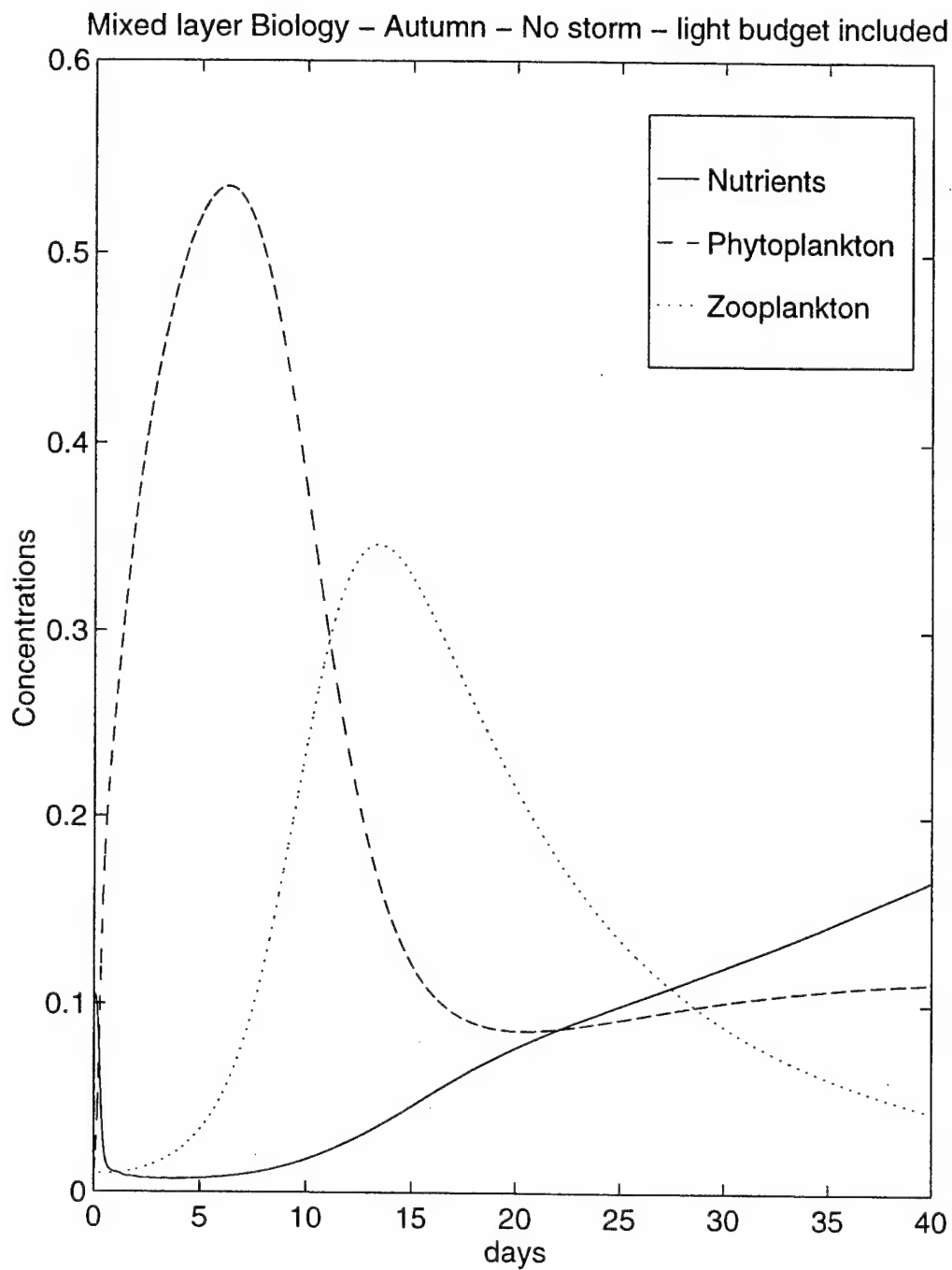
Figure 11a. Mixed layer biology initialized in autumn calm conditions ($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) and a strongly stratified water column with a light budget included.

Figure 11b. TKE, mixed layer depth and horizontal currents initialized in autumn calm conditions (Q = 0.001 cal/cm²/s and τ = 0.5 dynes/cm²) and a strongly stratified water column with light budget included.
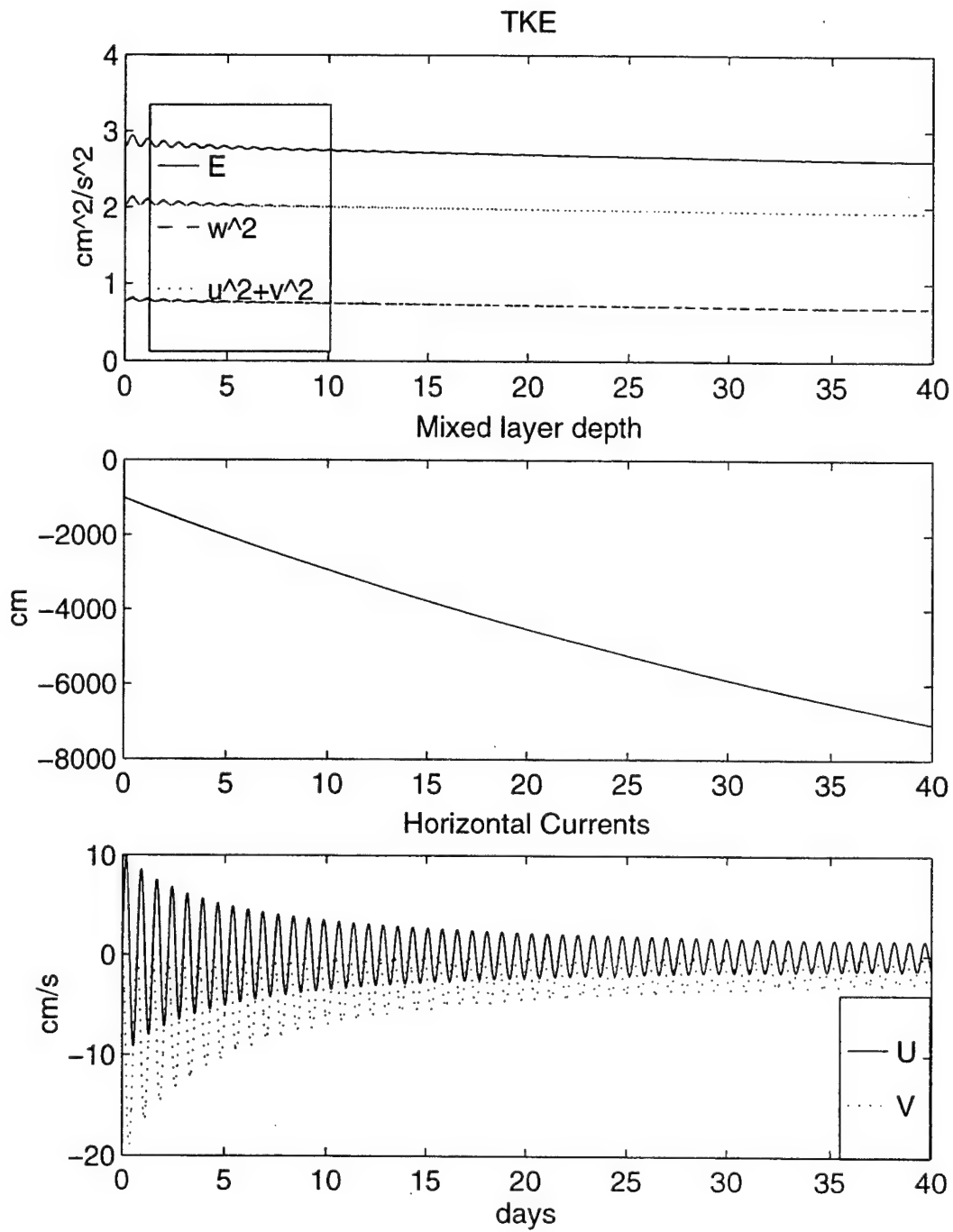
The next case was initialized with the same initial conditions as in the previous run. On day 20 a storm was initiated with a wind stress $(\tau) = 2.0$ dynes/cm^2 and net upward heat flux of $(\mathbf{Q}) = -0.006$ cal/cm^2/s. On day 22 the wind stress was returned to pre-storm conditions and the heat flux reduced to $(\mathbf{Q}) = -0.001$ cal/cm^2/s in the upward direction.

Figure 12a shows the nutrient level growing rapidly when the storm is initiated because of the entrainment of nutrients from below the mixed layer as a result of increased turbulence. Figure 12b show the mixed layer deepening rapidly after day 20 to a maximum depth of 400 m in 40 days. As a result of this deep mixed layer the light cannot provide the PAR to maintain the growth of phytoplankton and subsequently the zooplankton, which both approach zero.

This case demonstrates the definite necessity of a light budget to accurately model biological components.
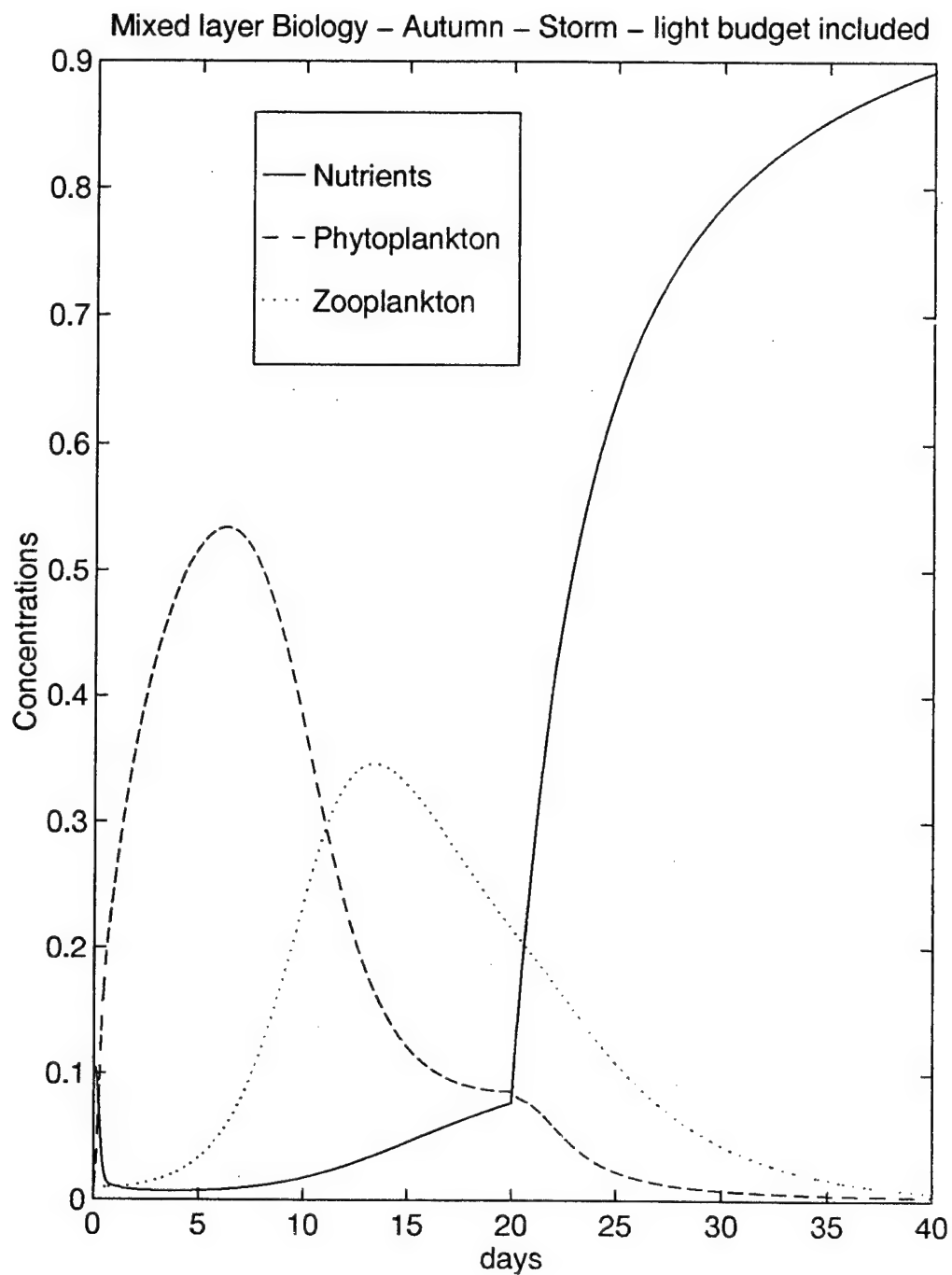
Figure 12a. Mixed layer biology initialized in calm autumn conditions($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) with storm induced on day 20 ($Q = -0.006$ cal/cm^2/s and $\tau = 2.0$ dynes/cm^2) and a strongly stratified water column including a light budget.

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Figure 12b. TKE, mixed layer depth and horizontal currents initialized in calm autumn conditions($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) with storm induced on day 20 ($Q = -0.006$ cal/cm^2/s and $\tau = 2.0$ dynes/cm^2) and a strongly stratified water column including a light budget.
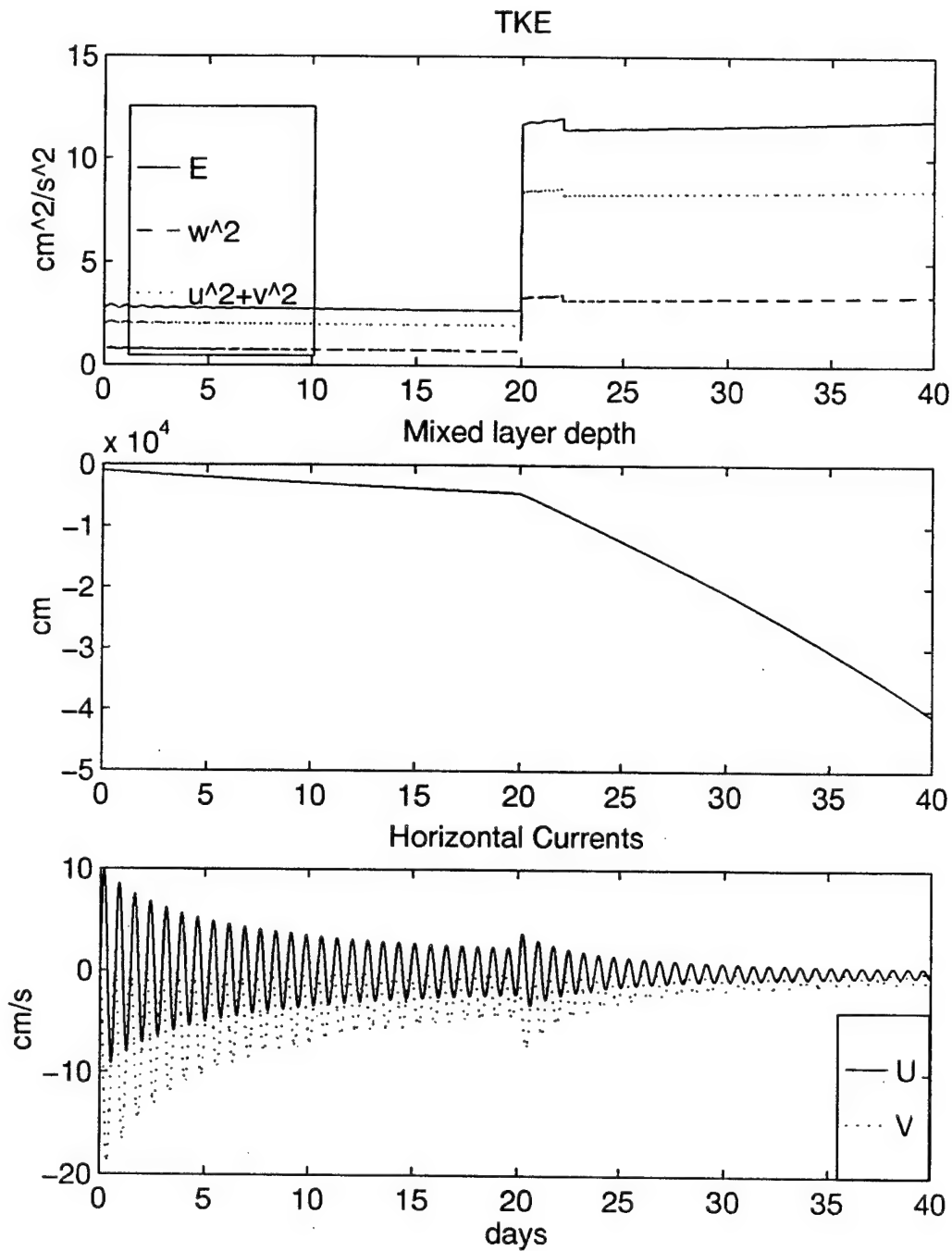
45

The next case represents winter conditions with a light budget included in the NPZ model. The model was initialized using downward heat flux $(\mathbf{Q}) = 0.001$ cal/cm^2/s and wind stress $(\tau) = 1.0$ dynes/cm^2. The initial nutrient concentration was 1.0. The water column was weakly stratified with temperature jump of 0.1 ^{o}C at the base of the mixed layer.

Although the biological results in Figure 13a appear to be unrealistic, the response of the model is accurate. Figure 13b shows the mixed layer deepening rapidly which exceeds 100 m in less than three days. As a result of this rapidly deepening mixed layer the growth of phytoplankton is decreased and an increase in the level of nutrients occurs quickly after an initial consumption from the only growth of phytoplankton in this run. The zooplankton never get the chance to grow since the phytoplankton do not achieve a very high level. Also of note in Figure 13b is the rapid damping of the horizontal currents, which is a result of the rapidly deepening mixed layer.

This case was rerun with a storm condition induced at day 20; however, the results are not shown since mixed layer deepens rapidly as in the previous run and when the storm was initialized it deepened to unrealistic depths.
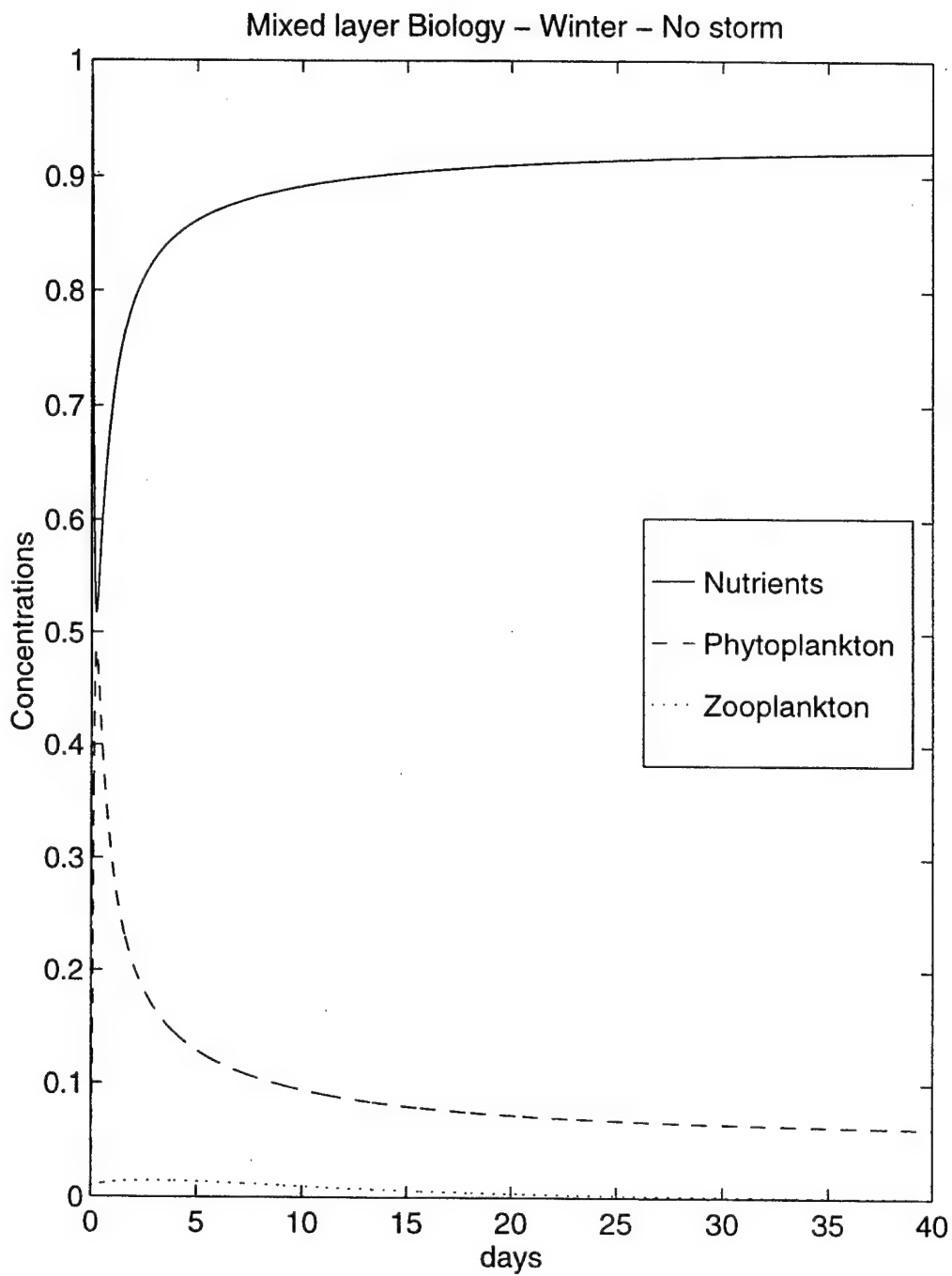
Figure 13a.   Mixed layer biology initialized in winter conditions ($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) and a weakly stratified water column with a light budget included
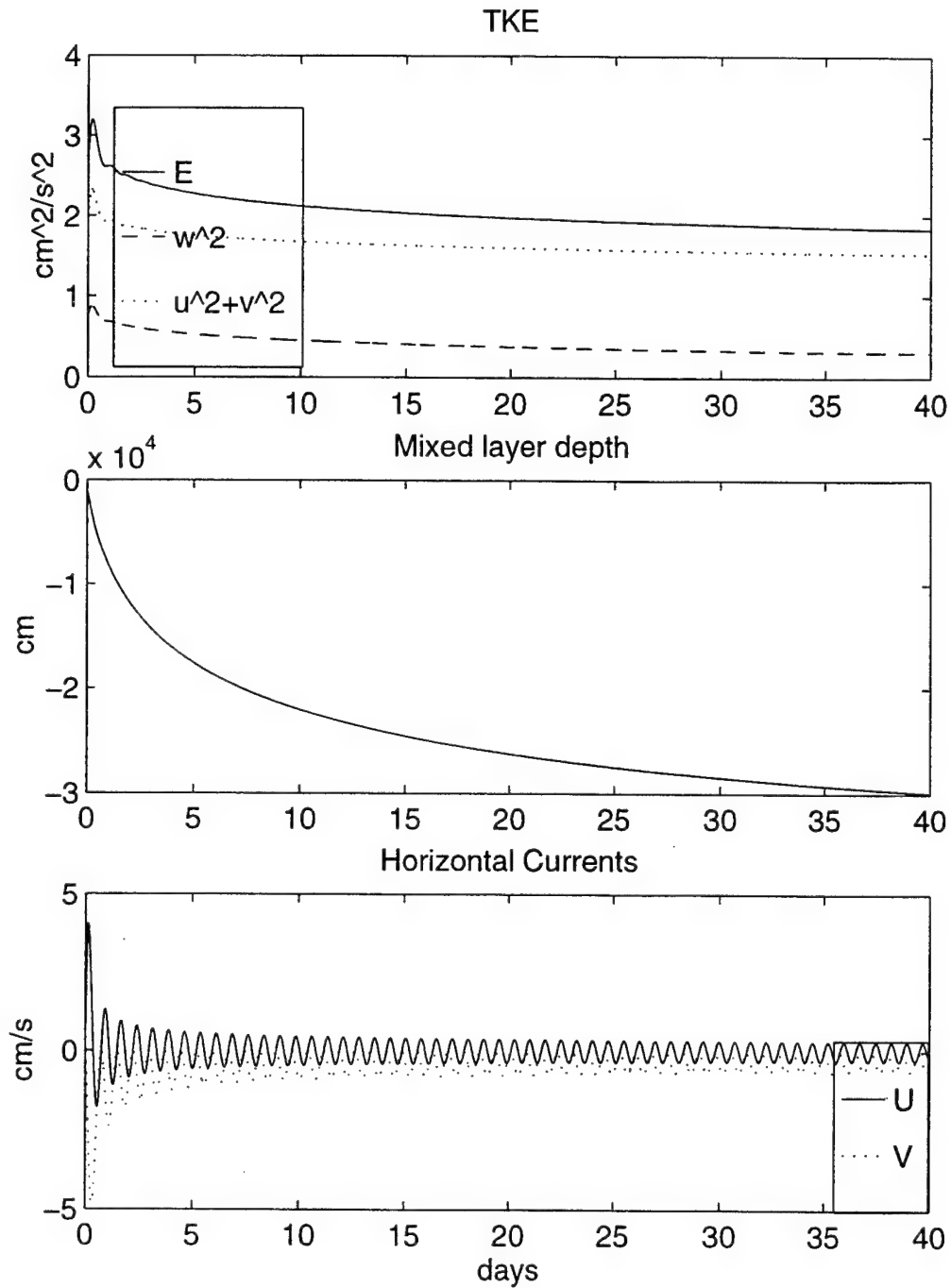
Figure 13b. TKE, mixed layer depth and horizontal currents initialized in winter conditions (Q = 0.001 cal/cm^2/s and τ = 1.0 dynes/cm^2) and a weakly stratified water column with light budget included.

In the next series of runs the NPZD model was used. This model included terms for detritus and light. The first of these runs is the basic autumn previously mentioned with $(Q) = 0.001$ cal/cm^2/s and $(\tau) = 1.0$ dynes/cm^2. The initial nutrient level is 0.1 and the water column is strongly stratified at the base mixed layer with a temperature jump of 5.0 °C. The NPZD runs are conducted for 12 days vice 40 days for the NPZ model since the NPZD model approaches a steady state much more quickly than the NPZ model.

Figure 14a displays the evolution of the nutrients, phytoplankton, zooplankton and detritus for this NPZD model run. The nutrient level peaks followed by a phytoplankton peak. As a result of this phytoplankton peak, the nutrient level shows an associated dip from the increased phytoplankton grazing. The phytoplankton concentration then dips at day five as a result of the growing zooplankton. The detritus concentration increases to a value of just greater than 0.05 in five days. The entire system approaches a steady state in approximately seven days.

Figure 14b displays the TKE, mixed layer depth and horizontal currents for this 12 day run. The reader will note from the figure that the mixed layer deepens from 10 m to 32 m in 12 days, so light limiting is not a major factor in this case.

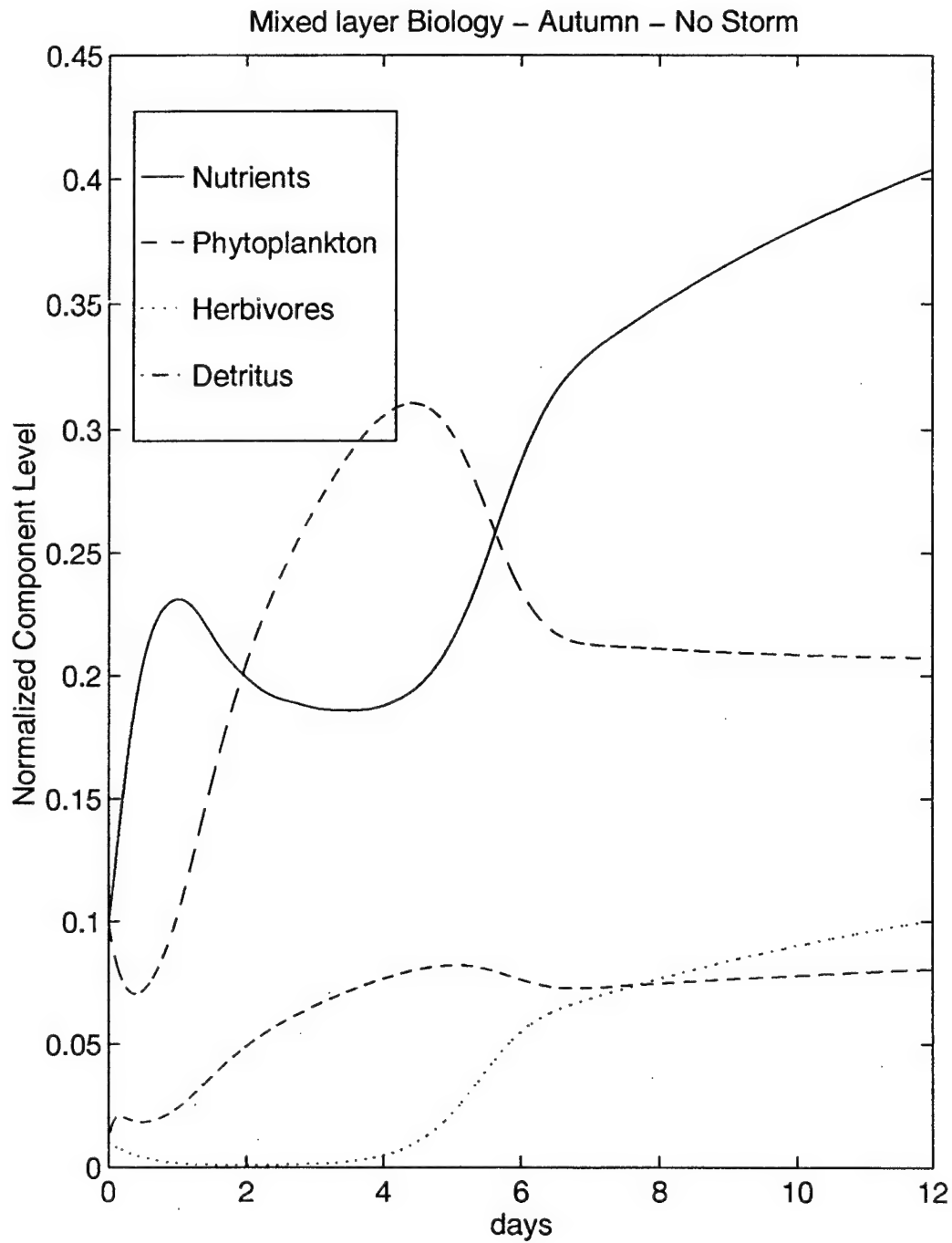Figure 14a. NPZD mixed layer biology initialized in autumn calm conditions (Q = 0.001 cal/cm^2/s and τ = 1.0 dynes/cm^2) and a strongly stratified water column with a light budget included.

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Figure 14b. NPZD TKE, mixed layer depth and horizontal currents initialized in autumn calm conditions (Q = 0.001 cal/cm²/s and τ = 1.0 dynes/cm²) and a strongly stratified water column with light budget included.
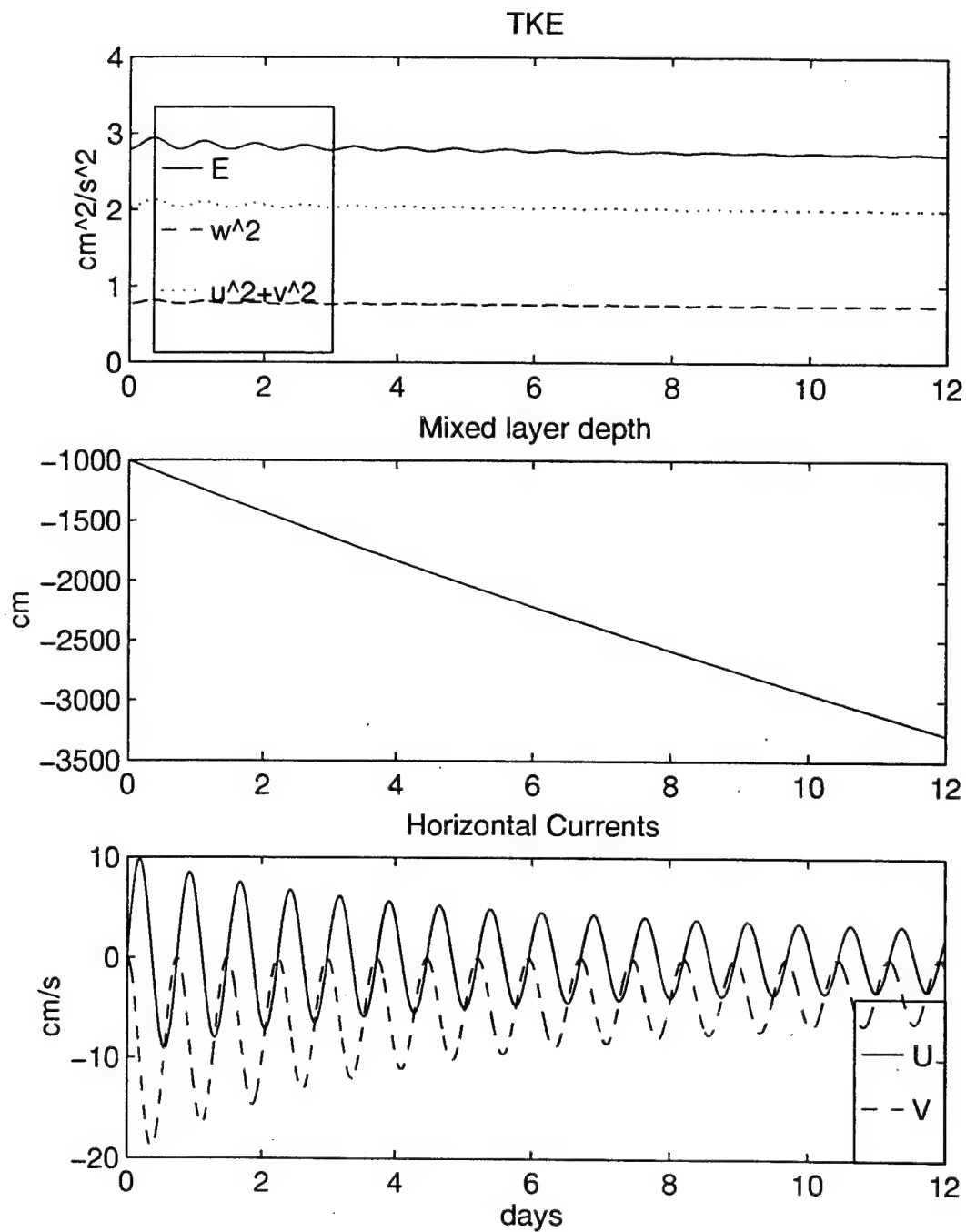
The next case is initialized with the same initial conditions as in the last case. For this run a storm condition $(\mathbf{Q}) = -0.006$ cal/cm^2/s and $(\tau) = 2.0$ dynes/cm^2 started on day five and stopped on day seven. The post-storm conditions were $(\mathbf{Q}) = -0.001$ cal/cm^2/s and $(\tau) = 1.0$ dynes/cm^2.

Figure 15a displays the NPZD mixed layer biology for this storm case. The most striking feature in this plot is the rapid increase in nutrients when the storm is initialized. Also of interest is the rapid decay of phytoplankton, zooplankton and detritus after the storm is started. An investigation of Figure 15b reveals the reason for this response. The mixed layer, deepening slowly for the first five days, begins to rapidly deepen after the storm initialization. As was shown in the previous runs with the NPZ model with the light budget, when the mixed layer deepens beyond approximately 100 m the phytoplankton growth is essentially cut off.

Figure 15b also reveals a dramatic jump in TKE and a strong damping of horizontal currents once the storm condition is started as a result of the rapidly deepening mixed layer.
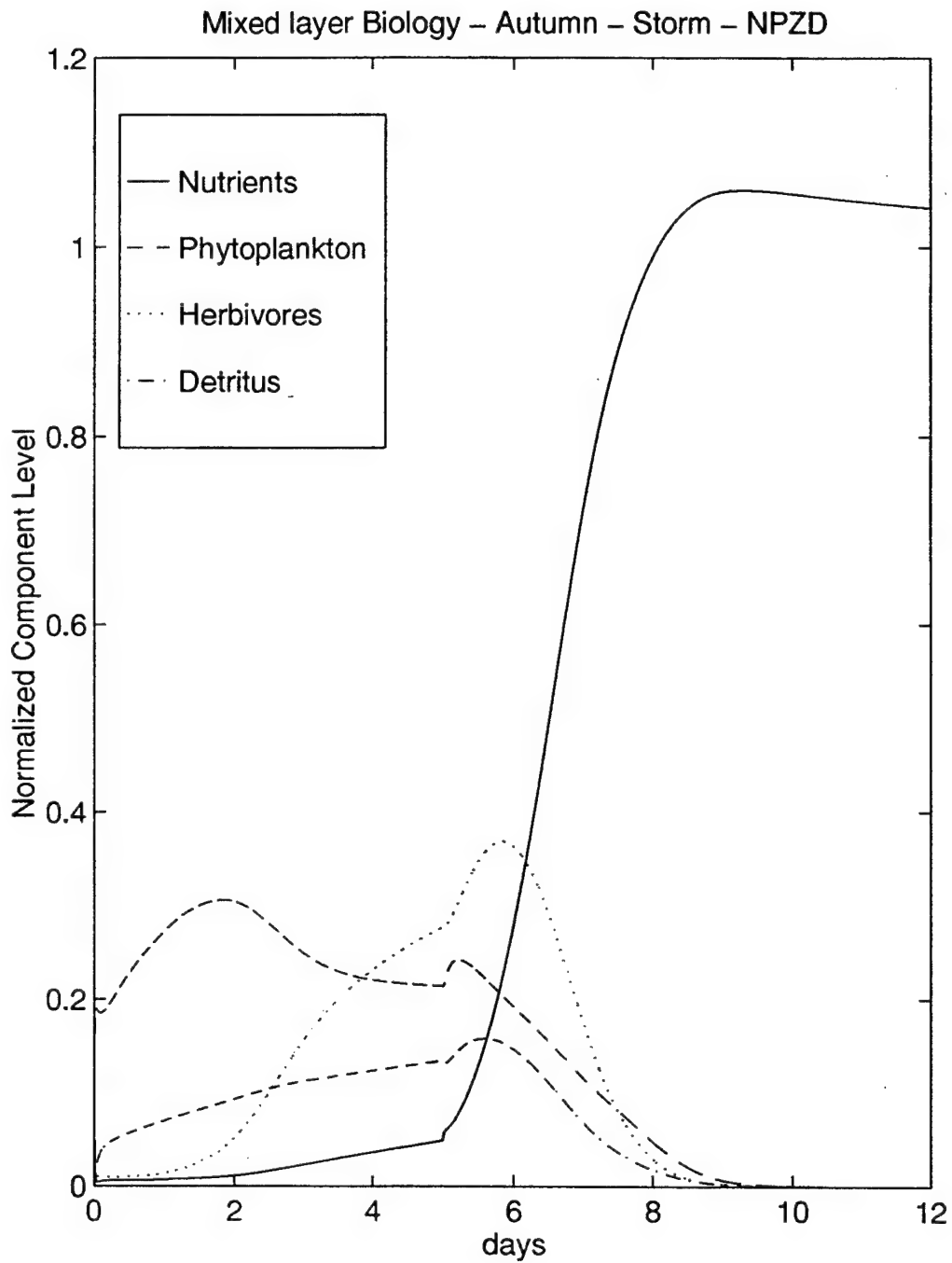
Figure 15a. NPZD mixed layer biology initialized in calm autumn conditions($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) with storm induced on day five ($Q = -0.006$ cal/cm^2/s and $\tau = 2.0$ dynes/cm^2) and a strongly stratified water column including a light budget.

Figure 15b. NPZD TKE, mixed layer depth and horizontal currents initialized in calm autumn conditions($Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2) with storm induced on day five ($Q = -0.006$ cal/cm^2/s and $\tau = 2.0$ dynes/cm^2) and a strongly stratified water column including a light budget.

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For the final case, the NPZD model was forced with winter conditions $Q = 0.001$ cal/cm^2/s and $\tau = 1.0$ dynes/cm^2. The water column is weakly stratified with a temperature jump of 0.1 $^{\circ}$C and the initial nutrient concentration level of 1.0.

Figure 16a displays the NPZD mixed layer biology for this winter time case. This plot indicates a very rapid approach to a steady state condition. As in previous cases the cause for this rapid change is the quickly deepening mixed layer as is displayed in Figure 16b. The phytoplankton concentration instantaneously grows to a maximum value and then decays very rapidly on the order of one day. Similarly the nutrient concentration profile is the inverse of the phytoplankton profile. The zooplankton and detritus also peak rapidly with much lower concentration values compared to the phytoplankton.

Figure 16b shows the TKE, mixed layer depth and horizontal currents for this run. Of interest is the rapid dampening of the horizontal currents as the mixed layer deepens rapidly.

This case was also run with a storm condition induced; however, when the storm was induced the mixed layer again deepened very rapidly to an unrealistic depth. For this reason the results of that run are not described here.
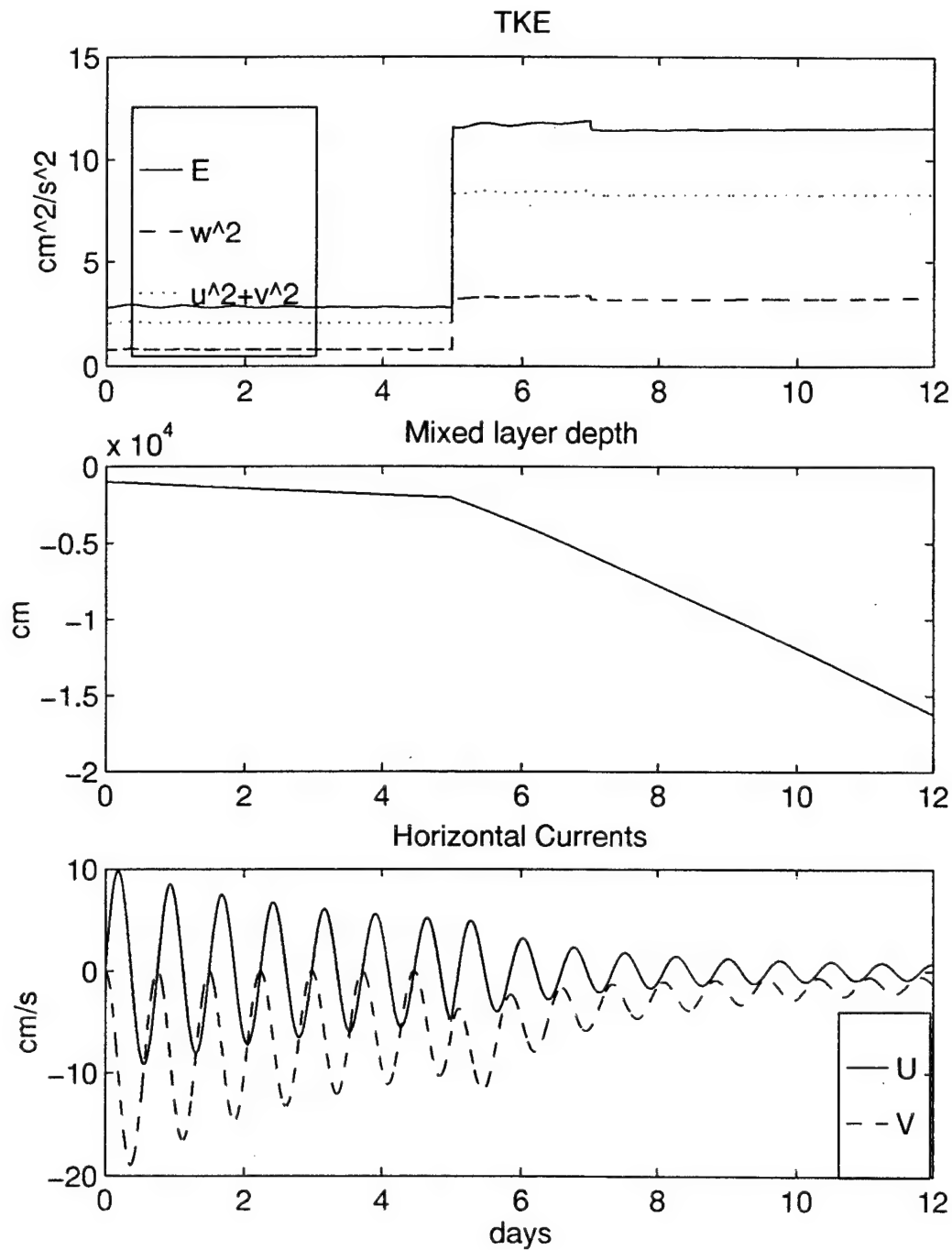
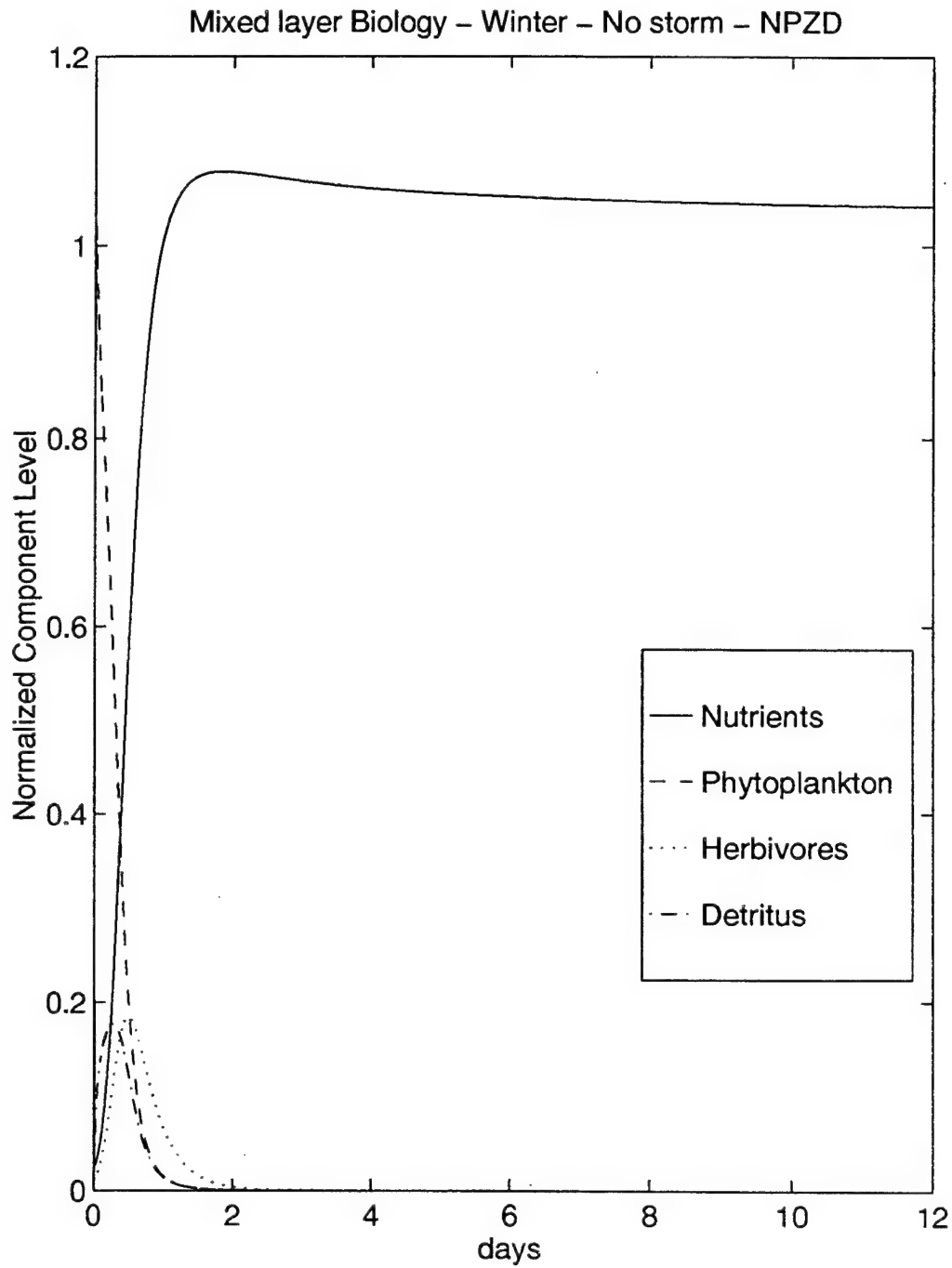Figure 16a. NPZD mixed layer biology initialized in winter conditions (Q = 0.001 cal/cm^2/s and τ = 1.0 dynes/cm^2) and a weakly stratified water column with a light budget included.

Figure 16b. NPZD TKE, mixed layer depth and horizontal currents initialized in winter conditions (Q = 0.001 cal/cm^2/s and τ = 1.0 dynes/cm^2) and a weakly stratified water column with light budget included.
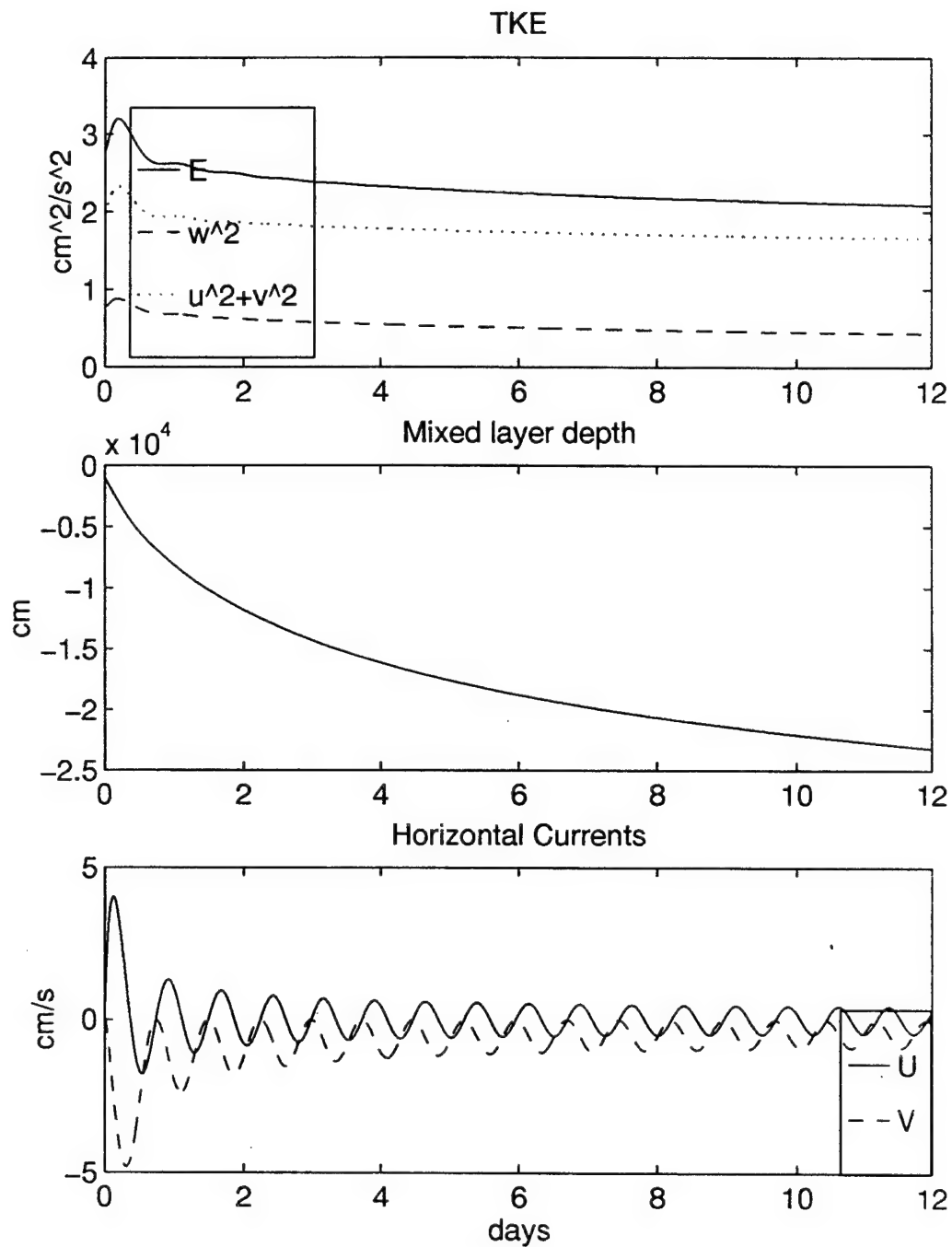
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V. CONCLUSIONS AND AREAS FOR FURTHER RESEARCH

Many conclusions may be drawn from the results presented in the previous chapter. The most dramatic result which was seen throughout the model simulations was the fact that nutrient concentration levels increase rapidly as turbulence spins up because of the entrainment of the nutrients from below the mixed layer.

It is also evident that stronger turbulence promotes a rapid approach to steady state conditions. This is result of the additional nutrients being introduced to the system and the subsequent rapid increase of phytoplankton and zooplankton. Surprisingly, the increasing nutrients drive the system to a near steady state more rapidly but do not increase the overall concentration levels of nutrients, phytoplankton or zooplankton.

The light limiting the growth of phytoplankton is the major limiting factor below 100 m in the experiments run here. This depth would depend greatly upon the clarity of the water mass being studied. It is evident from these results that future coupled/physical biological modeling must include a light budget.

From the results presented here, it is obvious that turbulence induces a biological response. This response could be one cause of the initiation of a bloom. This finding is in concurrence with the findings of Oguz et al. (1996) in which they found that the onset of a bloom in the Black Sea was, at least, partially dependent upon local mixing.

As stated in Doney et al. (1996) our knowledge of planetary boundary layer physics and biological vertical structure and fluxes is limited. This fact dictates that the future of physical/biological modeling requires the improvement of the physical half of the model before we can attempt to make major improvements to the biological half. As

such, for advancements to take place in this field we must improve our knowledge of turbulence fields and our ability to accurately model them. As our knowledge of the complex interactions between biological organisms improves, so will our ability to build the groundwork for improved biological modeling.

The physical/biological modeling field will be improved with the development of a high resolution in-situ data set, including detailed measurements of biological and physical parameters through a transient event, much like the physical data set collected by Smythe et al. (1997). This would be a great step in the advancement of model tuning and verification.

LIST OF REFERENCES

Aksnes, D.L. and J.K. Egge, A theoretical model for nutrient uptake in phytoplankton, *Marine Ecology Progress Series, 70*, 65-72, 1991.

Aksnes, D.L., U. Lie, A Coupled Physical-Biological Pelagic Model of a Shallow Sill Fjord, *Estuarine, Coastal and Shelf Science, 31*, 459-486, 1990.

Cullen, J.J., On models of growth and photosynthesis in phytoplankton, *Deep-Sea Research, 37*, No. 4, 667-683, 1990.

Davis, C.S. and J.H. Steele, Biological/Physical Modeling of Upper Ocean Processes, *WHOI Technical Report*, WHOI-94-32, 1994.

Doney, S.C., D.M. Glover, and R.G. Najjar, A new coupled, one-dimensional biological-physical model for the upper ocean: Applications to the JGOFS Bermuda Atlantic Time-series Study (BATS) site, *Deep-Sea Research II, Vol 43*, No. 2-3, 591-624, 1996.

Fasham, M.J.R., H.W. Ducklow, and S.M. McKelvie, A nitrogen-based model of plankton dynamics in the oceanic mixed layer, *Journal of Marine Research, 48*, 591-639, 1990.

Franks, P.J.S., J.S. Wroblewski, G.R. Flierl, Behavior of a simple plankton model with food-level acclimation by herbivores, *Marine Biology, 91*, 121-129, 1986.

Frost, B.W., Grazing control of phytoplankton stock in the open subarctic Pacific Ocean: a model assessing the role of mesozooplankton, particularly the large calanoid copepods *Neocalanus* spp., *Marine Ecology Progress Series, 39*, 49-68, 1987.

Frost, B.W., A modelling study of processes regulating plankton standing stock and production in the open subarctic Pacific Ocean, *Progressive Oceanography, 32*, 17-56, 1993.

Garwood, R.W., An Oceanic Mixed Layer Model Capable of Simulating Cyclic States, *Journal of Physical Oceanography, 7*, No. 3, 455-468, 1977.

Ivlev, V.S., Experimental ecology of the feeding of fishes. Pischepromizdat, Moscow. 302 pp., 1955 (translation from Russian by D. Scott) New Haven, Yale University Press, 1961.

Mayzaud, P. and S.A. Poulet, The importance of the time factor in the response of zooplankton to varying concentrations of naturally occurring particulate matter, *Limnol Oceanography, 23*, 1144-1154, 1978.

Mellor, G.L.and T. Yamada, Development of a Turbulence Closure Model for Geophysical Fluid Problems, *Reviews of Geophysics and Space Physics, Vol. 20*, No. 4, 851-875, 1982.

Moisan, J.R., E.E. Hofmann, D.B. Haidvogel, Modeling nutrient and plankton processes in the California coastal transition zone – A three-dimensional physical-bio-optical model, *Journal of Geophysical Research, 101*, No. C10, 22,677-22,691, 1996.

Oguz, T., H. Ducklow, P. Malanotte-Rizzoli, S. Tugrul, N.P. Nezlin, and U. Unluata, Simulation of annual plankton productivity cycle in the Black Sea by a one-dimensional physical-biological model, *Journal of Geophysical Research, Vol 101*, No. C7, 16,585-16,599, 1996.

Price, J.F., R.A. Weller and R. Pinkel, Diurnal Cycling: Observations and Models of the Upper Ocean Response to Diurnal Heating, Cooling, and Wind Mixing, *Journal of Geophysical Research, 91*, No. C7, 8411-8427, 1986.

Skogen, M.D., E. Svendsen, J. Bernsten, D. Aksnes, and K.B. Ulvestad, Modelling the Primary Production in the North Sea using a Coupled Three-dimensional Physical-Chemical-Biological Ocean Model, *Estuarine, Coastal and Shelf Science, 41*, 545-565, 1995.

Smythe, W.D., P.O. Zavialov, J.N. Moum, Decay of turbulence in the upper ocean following sudden isolation from surface forcing, *Journal of Physical Oceanography, 27*, 810-822, 1997.

Steel, J. (1977) Ecological Modelling of the Upper Layers. In: *Modelling and Prediction of the Upper Layers of the Ocean*, E.B. Kraus, editor, Pergamon Press, 243-250.

Stone, R.E., Deep mixed layer entrainment, *Naval Postgraduate School Master's Thesis*, 1997.

Stramska, M. and T.D. Dickey, Modeling phytoplankton dynamics in the northeast Atlantic during the initiation of the spring bloom, *Journal of Geophysical Research, 99*, No. C5, 10,241-10,253, 1994.

Traganza, E.D., D.G. Redalje and R.W. Garwood, chemical flux, mixed layer entrainment and phytoplankton blooms at upwelling fronts in the California coastal zone, *Continental Shelf Research, Vol 7*, No. 1, 89-105, 1987.

White, J.W., Optical effects on ocean mixed layer dynamics, *Naval Postgraduate School Master's Thesis*, 1991.

Wroblewski, J.S., A model of phytoplankton plume formation during variable Oregon upwelling, *Journal of Marine Research,* 35, 357-394, 1977.

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